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CONTROL DATA

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CONTROL DATA CORPORATION

A FEASIBILITY STUDY FOR MEASURING STRATOSPHERIC TURBULENCE USING METRAC™ POSITIONING SYSTEM

By

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ABSTRACT

This report demonstrates the feasibility of obtaining measurements of Lagrangian turbulence at stratospheric altitudes by using the METRAC System to track constant-level balloons. The basis for current estimates of diffusion coefficients are reviewed and it is pointed out that insufficient data is available upon which to base reliable estimates of vertical diffusion coefficients. It is concluded that diffusion coefficients could be directly obtained from Lagrangian turbulence measurements. The METRAC balloon tracking system is shown to possess the necessary precision in order to resolve the response of constant-level balloons to turbulence at stratospheric altitudes. A small sample of data recorded from a tropospheric tetroon flight tracked by the METRAC System is analyzed to obtain estimates of small-scale three-dimensional diffusion coefficients. It is recommended that this technique be employed to establish a climatology of diffusion coefficients and to ascertain the variation of these coefficients with altitude, season and latitude.

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES

1. INTRODUCTION

The diffusion of pollutants introduced into the stratosphere by supersonic transports has been the subject of an extensive research effort coordinated and sponsored by the Department of Transportation. This research program known as CIAP (Climatic Impact Assessment Program) has brought the resources of several government agencies, universities, and private institutions to bear on an evaluation of the danger of a depletion of the earth's ozone shield as a result of the operation of a fleet of supersonic transport aircraft flying at altitudes from 18 to 21 km in the stratosphere. One of the central objectives in evaluating this danger has been the development of realistic models which incorporate both the effects of turbulent diffusion and the effects of chemical transformations. These models can be one-dimensional, two-dimensional or three-dimensional. The two-dimensional and three-dimensional models are, of course, more realistic than one-dimensional models but they require more time for development and consume much more time on the computer. In all of these models diffusion coefficients are required to account for the turbulent spread of effluents. In order to make the problem tractable it is necessary to consider several different time and space scales. The smallest scale of interest is the scale of the wake of the stratospheric transport. The wake itself can be subdivided into jet, vortex and dispersion regimes (Poppoff, Farlow and Anderson, 1974). In the dispersion regime a transition occurs from aircraft induced dispersion to dispersion dominated by the turbulence of the natural stratosphere. This occurs between 100 and 1000 sec after passage of the aircraft. At ten minutes after passage of the SST the width of the wake is about 500 meters and its depth is about 16 meters (Hoshizaki, Anderson and Conti, 1972).

The smallest atmospheric scales of interest in the dispersion of the aircraft wake are on the order of five minutes and 300 meters. Beyond these scales, diffusion is controlled by stratospheric wind fields and the

wake spreads and mixes with other wakes. After several weeks the problem becomes global in scope.

This report is directed toward an examination of a new approach to the *in situ* measurement of small-scale diffusion coefficients in the stratosphere. This new approach is to accurately track constant-level balloons in three dimensions using the METRAC System and to deduce diffusion coefficients from an analysis of Lagrangian turbulence statistics. The METRAC System is a radio-location system which employs the Doppler principle in order to accurately position an expendable radio transmitter. Direct measurement of small-scale vertical motions in the stratosphere using METRAC may provide the only means for direct determination of vertical diffusion coefficients.

The nature of stratospheric turbulence and the basis for current estimates of stratospheric diffusion coefficients are presented in Chapter 2 and Chapter 3. A review of balloon techniques for obtaining turbulence measurements and diffusion coefficients is presented in Chapter 4. Chapter 5 contains a description of the METRAC balloon-tracking system and Chapter 6 contains an analysis of a sample of data from a tetroon tracked in the troposphere by the METRAC system. Some considerations of the application of the METRAC system for tracking constant-level balloons in the stratosphere are discussed in Chapter 7. Conclusions and recommendations are given in Chapter 8.

2. NATURE OF STRATOSPHERIC TURBULENCE

In order to understand the scale-dependent spread of atmospheric pollutants in the stratosphere it is necessary to review the nature of turbulence in the stratosphere. Classical turbulence theory has been developed for statistically homogeneous, isotropic fields of turbulence. Although turbulence approaches the homogeneous isotropic state in the lower atmosphere, it can be isotropic only on the smallest scales in the stratosphere ($\ell \sim 10$ m, $\tau \sim 100$ sec). This is primarily due to the stable thermal stratification which inhibits vertical motion. Thus it is common experience

that stratospheric effluents diffuse more rapidly in the horizontal than they do in the vertical. The nature of turbulence in a stably stratified fluid under the influence of the gravitational force is intermittent in time and inhomogeneous in space. Dynamically, turbulence develops in local zones of strong shear. The Richardson number is commonly used as a measure of the dynamic stability of a stratified shear flow. When the local gradient Richardson number

$$Ri_\ell \equiv \frac{\frac{g}{\theta}\frac{\partial \theta}{\partial z}}{\left(\frac{\partial U}{\partial z}\right)^2} \qquad (\theta \text{ is potential temperature})$$

is reduced below 1/4, an instability and transition to turbulence may occur. The resulting turbulence tends to destroy gradients within the turbulent layer and concentrate them at the boundary. Thus, statically stable zones are often found to contain much small-scale layered structure; with weakly turbulent zones separated by stable laminae. Gradients are concentrated in the stable laminae which occasionally break down and become turbulent. This structure is typically found in the stably stratified ocean on a very small scale. In the thermocline region stable laminae may be on the order of a few tens of cm thick [Woods (1969)]. In the stratosphere a layered structure also exists but it has not been possible to observe this structure in the same detail as in the ocean.

In order to model the spread of stratospheric pollutants in three dimensions it is necessary to parameterize the effect of turbulent diffusion. Because of the anisotropic nature of stratospheric turbulence it is important to consider separately vertical and horizontal diffusion. If it were possible to record an infinitely long time series of stratospheric winds, analysis would probably yield a spectral peak of the horizontal wind spectrum

in the large-scale (synoptic and global scale) end of the spectrum with a decrease in energy toward smaller scales and a second peak near the micro-scale. This is shown schematically in Fig. 1 adapted from Vinnichenko (1970). The existence of the meso-scale gap observed by Van Der Hoven (1957) in the boundary layer has been explained on theoretical grounds by Fiedler and Panofsky (1970). Observations are not available to confirm its existence in the free atmosphere. If direct vertical velocity measurements were available in the free atmosphere in a time series, an analysis would reveal a much different spectral distribution than for the horizontal components of velocity. In the asymptotic limit of the smallest scales the horizontal and vertical velocity spectra would appear quite similar. At larger scales, however, the vertical velocity spectrum would contain a negligible amount of energy compared to the horizontal component shown schematically in Fig. 1. In fact, the peak of vertical velocity spectra would occur on a time scale of only a few minutes [Panofsky (1969)].

The different distributions of vertical and horizontal turbulent kinetic energy are responsible for the different rates of spread of pollutants in vertical and horizontal directions. It is generally understood that maximum spread or diffusion occurs on or above the scale of maximum turbulent energy. This view is consistent with scale dependent diffusion coefficients which increase with scale through regions of strong turbulent energy and which approach constant values at scales beyond which there is little additional turbulent kinetic energy. Thus, schematically as shown in Fig. 2, adapted from Bauer (1974), the lateral diffusion coefficient increases with scale from 10^2 cm^2 s^{-1} at a 10 second time scale to 10^9 cm^2 s^{-1} above 10^6 sec. The vertical diffusion coefficient increases from 10^2 cm^2 s^{-1} at 10 sec to only 10^4 cm^2 s^{-1} above 10^3 sec. Above 10^3 sec the vertical diffusion coefficient approaches its asymptotic upper limit.

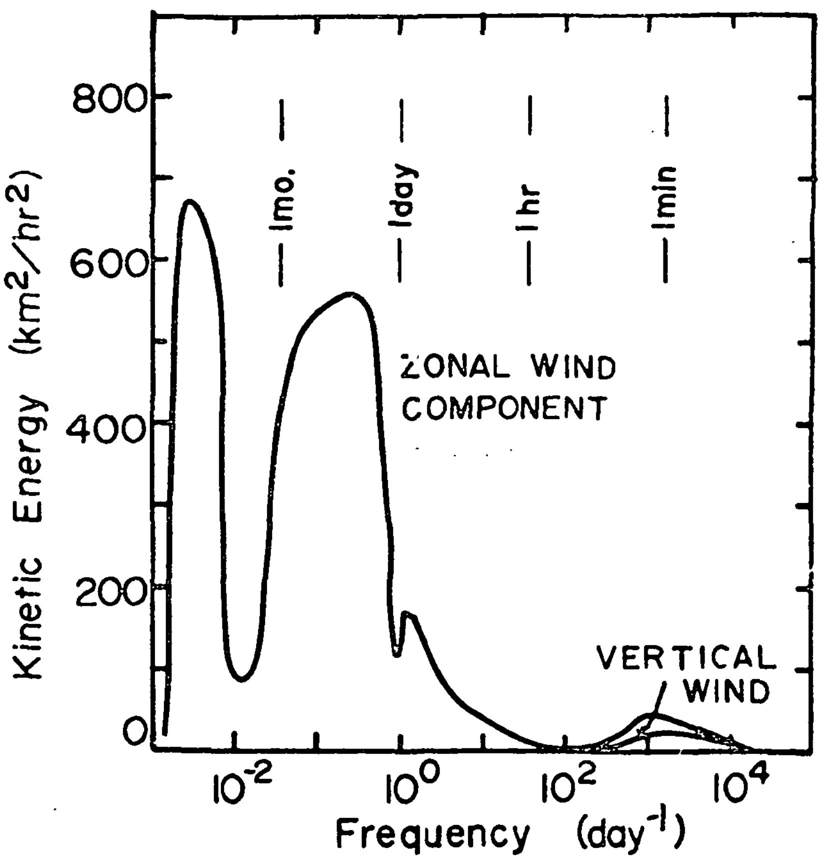

Figure 1. Schematic representation of frequency spectra of horizontal and vertical velocities in the free atmosphere (Zonal wind spectrum adopted from Vinnichenko, 1970).

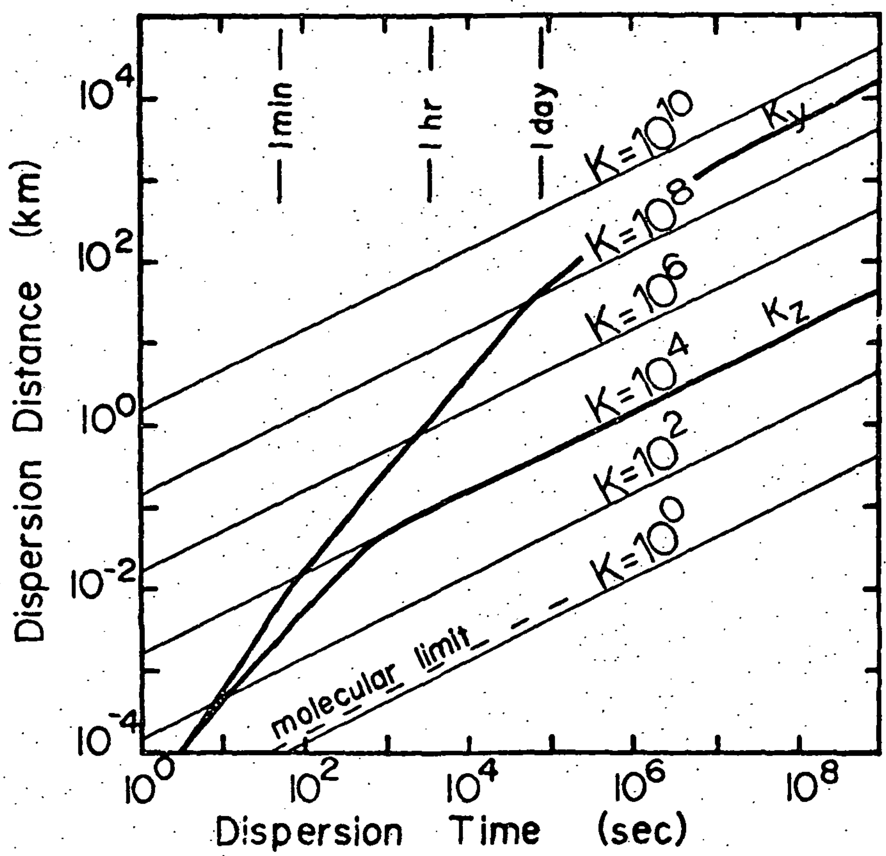

Figure 2. Schematic representation of the variation of lateral and vertical diffusion coefficients with diffusion time (after Bauer, 1974).

3. REVIEW OF STRATOSPHERIC TURBULENCE MEASUREMENTS AND THE BASIS FOR ESTIMATES OF STRATOSPHERIC DIFFUSION COEFFICIENTS

In the course of the CIAP program an effort has been made to review the sources of stratospheric turbulence measurements and to infer stratospheric diffusion coefficients. The results of such a study have been reported by Bauer (1974). On the small scale, turbulence measurements have been made and diffusion coefficients inferred from aircraft and from the dispersal of smoke puffs. On the global scale, diffusion coefficients have been inferred from measurements of radioactive material injected into the stratosphere from nuclear explosions and from global heat flux data. Below are reviewed the principal techniques for obtaining estimates of diffusion coefficients. Vertical diffusion coefficients are considered in more detail since their basis is much less certain than that of lateral diffusion coefficients.

3.1 AIRCRAFT MEASUREMENTS

Between 1964 and 1968 the Air Force recorded approximately 48 hours of turbulence data from specially instrumented U-2 aircraft flown between 15 and 21 km. These data were taken for the Air Force HICAT program and are the subject of several technical reports [Crooks, et al. (1967, 1968) and Ashburn, et al. (1968, 1969, 1970)] written for the Wright Patterson Air Force Flight Dynamics Laboratory.

Instrumentation aboard the HICAT U-2 aircraft provided measurement of all three components of velocity as well as temperature. The accuracy of these measurements is discussed by Crooks, et al. (1968) but a complete error analysis has never been made.

Lilly, Waco and Adelfang (1974) have recently reviewed the HICAT data in order to deduce estimates of stratospheric diffusion coefficients. The method used is as follows. First, the dissipation (ϵ) is estimated from composite spectra assuming an inertial subrange form for the spectral density function. An assumption that the flux Richardson number should be near 1/4 leads to the conclusion that buoyancy or heat flux is equal to one third of the dissipation. Then, if the usual Fickian relationship is assumed to hold between heat flux and temperature gradient, it follows that the diffusion coefficient for heat is

$$K_H = \frac{\epsilon}{3N^2} \tag{3.1}$$

where

$$N^2 = \frac{g}{\theta}\frac{\partial\theta}{\partial Z} \;. \tag{3.2}$$

N is the Brunt-Vaisala frequency, and θ is potential temperature. Now an isothermal stratosphere is assumed [with T = 210K, $N^2 = 4.6 \times 10^{-4}$ sec^{-2}] and the heat flux can be evaluated from the dissipation. This leads to an indirect estimate of diffusion coefficients from aircraft measurements of the velocity variance $v_i^2(k)$. The values of the estimated diffusion coefficients range from 4.8×10^3 cm^2 s^{-1} over water to 1.2×10^4 cm^2 s^{-1} over high mountains. Since these estimates are only applicable to regions of intermittent turbulence, a more representative diffusion coefficient was estimated by multiplying the above numbers by their probability of occurrence. The result is an estimate of an effective diffusion coefficient which ranges from 100 cm^2 s^{-1} over land to 640 cm^2 s^{-1} over high mountains. These estimates were made for turbulence on the scale of 610 meters which corresponds to a few seconds on the diffusion time scale of Bauer's diagram.

Some addidional turbulence data is available from stratospheric flights of Project Coldscan reported by MacPherson and Morrissey (1969, 1970) and from the Colorado LEE WAVE Experiment reported by Lilly, et al. (1971), and Lilly and Lester (1974). These data are not nearly as complete as the HICAT data reported above.

3.2 DISPERSION OF SMOKE PUFFS

Another source of small-scale turbulence data is provided from observations of the dispersion of smoke puffs and trails. This work is most significant since small-scale diffusion may be more naturally assessed in a Lagrangian context. The dispersion of smoke puffs was observed as part of the "High Altitude Dust Diffusion Project" at Holloman Air Force Base. Results of twenty experiments at altitudes ranging from 7.2 to 19.3 kilometers were reported by Kellogg (1956). Smoke puffs were created from the explosion of vials of titanium tetrachloride and water. These vials were attached to a train of rising balloons and were exploded by the closing of a baroswitch contact at pre-selected altitudes.

After the initial disturbance created by the explosion died down, the resultant smoke puff acted as a tracer and was tracked by a network of three phototheodolites. Later the growth of the smoke puff was deduced from a detailed hand analysis of photographic data. Specifically, the cloud edges were observed and the diameter of the cloud was determined as a function of time. After about six minutes the cloud became so tenuous that it was difficult to reliably measure the cloud diameter. In order to separate the effect of diffusion from the effect of wind shear the data was analyzed to determine the minimum diameter at each time. The average values of the minimum diameter are presented in Fig. 4 of Kellogg (1956). The puffs typically grew from 15 meters to 120 meters in six minutes. This

growth is consistent with a diffusion coefficient of 5×10^4 cm^2 s^{-1} for diffusion times of five minutes. There is no attempt in the analysis to differentiate between horizontal and vertical diffusion coefficients.

3.3 RADIOACTIVE TRACERS

There are three categories of radioactive material from nuclear explosions. These categories are radioactive products of the fission process, radioactive isotopes activated by neutron bombardment and unspent radioactive bomb material. A common tracer in the first category is strontium-90 which has been the subject of considerable study because of its long half-life and its potential health hazard. Carbon-14 is produced by neutron activation.

The commonly measured radioactive isotopes include strontium-90, carbon-14, tungsten-185, plutonium-238, cadmium-109, and rhodium-102. The first two isotopes are produced by every nuclear test whereas tungsten-185, cadmium-109, and rhodium-102 are special tracers which can be identified with certain tests. Plutonium-238 was injected into the atmosphere as a result of the burn-up of a navigational satellite with a radioactive power source.

Tracer data has been the subject of extensive analysis by a number of authors. The main features of the results are summarized by List and Telegadas (1969). Two periods have received the most attention. These are the periods of test moratoriums which were 1959-1961 and after January 1963.

Results of the analysis of tracer data are incomplete. However, some obvious conclusions can be drawn from available data. It is clear that the spread of radioactive material is dependent upon altitude, latitude and season. Residence times give an indication of the rate of vertical transport of radioactive tracers. In the lower equatorial stratosphere tungsten-185

tracers produced in 1958 exhibited a residence time of eight months. Tracer data, however, did not become available routinely above 20 km until October 1964, so that a reliable estimate of residence time for material injected into the upper stratosphere is not available. Nevertheless, Peterson (1970) has given an estimate of two years for the residence time there. Russian tests in the polar regions in 1958 produced tracers which were confined below 15 km from which it was concluded that residence time for radioactive materials injected into the lower polar stratosphere is about five months (Peterson, 1970).

One of the difficulties in interpreting the results of tracer dispersion is that the tracer spreads due to the combined influence of large-scale circulations and diffusive mixing. List and Telegadas (1969) tentatively conclude from their analysis of tracer data that there are regions of the stratosphere which are dominated by advective transport and other regions dominated by mixing. The altitude range from 18 to 23 km, and the latitude belt from 25N to 25S is thought to be dominated by mixing. The entire summer stratosphere below 40 km is similarly thought to be dominated by mixing processes. List and Telegadas (1969) also conclude that at least between 25^{o} and 70^{o} latitude there is a strong mean descending motion in the winter stratosphere which dominates vertical transport.

There has been some concern expressed recently by Johnston, et al. (1975), that residence times deduced from particulate radioactive tracers are seriously underestimated. These authors advocate the use of carbon-14 as a tracer more representative of atmospheric motions. Carbon-14, of course, is found in CO_2 which is a gaseous tracer. The possibility that radioactive particulates will settle under the influence of gravity has been explored by Telegadas and List (1969). Settling rates are dependent upon the radius of the particle and the atmospheric density at the altitude being considered. Telegadas and List conclude that the settling rates are

too small to be important for the size of particles of interest below 25 to 30 km. Their conclusion is supported by an analysis of ratios of C^{14} to Sr^{90}. For example, between 1959 and 1962 the ratio of these two tracers is about constant with time at selected altitudes and latitudes. The fact that strontium-90 decreases with time more rapidly than carbon-14 during the second test moratorium is attributed to a difference in the initial vertical distributions of the two tracers. In this connection it is believed that Russian tests in 1961 produced much higher concentrations of C^{14} relative to Sr^{90} at altitudes above 25 km.

In view of the analysis of Telegadas and List (1969) and the radioactive tracer data reviewed above it is concluded here that the season and location of stratospheric injection are the determining factors in explaining the differences in residence time between C^{14} and particulate radioactive tracers pointed out by Johnston, et al. (1975).

3.4 ESTIMATES BASED ON HEAT FLUX DATA

Another source for diffusion coefficients is the work of Reed and German (1965). These authors compute seasonal global diffusion coefficients based on heat flux data and employing mixing length assumptions. Reed and German use the relation between vertical diffusion coefficient K_{ZZ} and lateral diffusion coefficient K_{YY} given by

$$K_{ZZ} = (\overline{\alpha^2} + \overline{\alpha'^2})K_{YY} \qquad (3.3)$$

where $\bar{\alpha}$ is the zonal mean slope of the mixing surface and $\overline{\alpha'^2}$ is its variance. The lateral diffusion coefficient K_{YY} is determined as a function of latitude from the variance of the meridional velocity component. From the heat flux and temperature gradient data it is possible to deduce the variation of $\bar{\alpha}$ with latitude but $\overline{\alpha'^2}$ is unknown. Reed and German use a representative equatorial K_{ZZ} value of 10^3 cm^2 s^{-1} deduced from the vertical

spread of radioactive tracers to obtain a value of $\overline{\alpha'^2}$ at the equator where $\bar{\alpha} = 0$. Then, "Not knowing how $\overline{\alpha'^2}$ varies with latitude and height, we assume that it remains constant." In this manner and from the previously deduced variation of $\bar{\alpha}$ with latitude a latitudinal variation of K_{ZZ} is generated.

There are several reasons to doubt the validity of the large-scale thermal diffusion coefficients K_{ZZ}. One reason is that the computation of K_{ZZ} is not direct but rather is adjusted to agree with a vertical diffusivity obtained from tracer studies. However, even if the approach of Reed and German gives valid vertical thermal diffusion coefficients it is not clear what relationship these thermal diffusion coefficients will have to the desired diffusion coefficients of passive additives. Diffusion coefficients are defined by an assumed linear relationship between flux and gradient. On the global scale, mixing surfaces and surfaces of constant potential temperature are inclined to the horizontal and do not share the same slope. Because of this situation, the gradients and fluxes may be quite different for heat than for a passive contaminant. The common assumption that diffusion coefficients should be nearly the same for different transported quantities is based on the hypothesis that the physical mechanism causing transport is common to the quantities being transported. That this is approximately true for small-scale turbulent transport is well documented. For large-scale transport it is not true that the physical mechanism responsible for vertical heat flux is common with mass flux.

3.5 DISCUSSION

The spread of material injected into the stratosphere is affected by the entire spectrum of atmospheric motions. For the horizontal spread the largest scale motions dominate the transport process and global diffusion rates have been estimated to be on the order of $10^9 cm^2 s^{-1}$. There are several ways in which this estimate can be supported. What needs clarification is how this global diffusivity is approached from the small-scale end

with increasing diffusion time.

Estimates of vertical diffusivities are in general not well supported because of insufficient data. Perhaps the primary reason for this state of affairs is the lack of direct measurement of atmospheric vertical velocities. We do know that mean vertical velocities are extremely small except on the smallest scales. If it is true that the spectrum of vertical velocity has its peak on the scale of a few minutes, it seems reasonable that this scale will dominate the vertical transport process. Unfortunately, there is just not enough data available to ascertain which scales of atmospheric motion do in fact dominate the vertical transport process.

The available information for estimating vertical diffusion coefficients in the stratosphere can be summarized as follows. Lilly, et al. (1974), have analyzed HICAT aircraft turbulence data and concluded that typical vertical diffusivities are on the order of 100 $cm^2\ s^{-1}$. The estimates of Lilly, et al. (1974) are considered valid for diffusion times on the order of 5-10 seconds. Kellogg (1956) has presented an analysis of the spread of smoke puffs from 18 stratospheric trials. His data is consistent with a diffusion coefficient of roughly $10^4 cm^2\ s^{-1}$ for diffusion times on the order of five minutes. Unfortunately it is not possible to separate vertical from horizontal transport in Kellogg's data so that the number quoted above may be an overestimate of vertical diffusivity. Finally, the most definitive data for basing estimates of diffusion coefficients comes from analyzing the spread of radioactive tracers. Vertical diffusion coefficients on the order of $1\text{-}5 \times 10^3\ cm^2\ s^{-1}$ (Machta and Telegadas, 1972) are consistent with the vertical transport of radioactive tracers. It has not been possible, with available data to obtain variations of vertical diffusion coefficients with latitude, altitude and season. The latitudinal variation of K_{ZZ} presented by Reed and German (1965) is based on several questionable assumptions and should not be used uncritically.

4. BALLOON TECHNIQUES FOR MEASURING TURBULENCE AND DETERMINING DIFFUSION COEFFICIENTS

Turbulence theory is developed in two frames of reference: Eulerian and Lagrangian. In the Eulerian frame a sensor is fixed in space and the time history of the fluctuating quantity being measured at that point is recorded. Time series analysis can be employed to analyze the frequency content of the turbulence and the mean velocity can be used according to Taylor's hypothesis to relate temporal to spatial variations. For obvious reasons the Eulerian frame is the preferred frame of reference for all surface boundary layer studies and extensive Eulerian turbulence data is available from tower mounted instruments. The Lagrangian frame follows the motion of elements or parcels of fluid. Turbulence measured in this moving frame is referred to as Lagrangian turbulence. Lagrangian turbulence is more basic to diffusion theory since it is in the Lagrangian frame that material actually diffuses.

Since most atmospheric measurements near the surface are taken in the Eulerian frame, considerable effort has been made by micrometeorologists to relate Eulerian turbulence statistics to Lagrangian turbulence statistics. Above the surface boundary layer it is much more difficult to collect meaningful in situ data. The lack of fixed platforms in the free atmosphere dictates the search for alternative techniques for measuring turbulence. The analysis of the spread of smoke puffs and radioactive tracers has already been discussed. These tracers offer the advantage of Lagrangian measurements but they do not readily lend themselves to quantitative analysis. Two techniques which do lend themselves to quantitative analysis are measurements from aircraft and rising balloons. Neither of these techniques yields an Eulerian or Lagrangian view of turbulence.

A far more powerful balloon technique for measuring turbulence in the free atmosphere has been developed in the past fifteen years. This method is to track constant-level balloons. Data so obtained can be readily

interpreted in terms of Lagrangian turbulence theory and the results are immediately applicable to diffusion theory.

Rising or floating balloons can be used to study air motion on a variety of scales. When attempting to extract turbulence information from balloon motion, two considerations are of vital importance. The accuracy with which the balloon can be positioned in space is the subject of Section 4.1. The degree to which the balloon motion provides an accurate indication of atmospheric motion is discussed in Section 4.2. The remainder of the chapter is concerned with two techniques for deducing diffusion coefficients from balloon measurements of turbulence.

4.1 REVIEW OF BALLOON TRACKING SYSTEMS

All balloon tracking systems currently available use one or a combination of the following techniques to obtain position or wind information:

1) Azimuth and elevation angles
2) Passive ranging (reflection)
3) Active ranging (transponders)
4) Thermodynamic height evaluation
5) Navigational aids
6) Doppler frequency measurements

The following paragraphs will summarize the wind finding or positioning capabilities of eight types of balloon tracking systems.

- <u>Single Theodolite</u>

Single theodolite measurements have been shown to yield reasonable wind profiles in the lowest few kilometers. Angular accuracy with optical theodolites can approach 0.01°, but observations are limited by cloud cover. Radio-theodolites have stated accuracies of only about 0.1° but are not

limited by cloud cover or other visual obstructions. Accuracy for both types of systems is angle dependent. The necessary assumption of a constant balloon ascent rate implies large wind errors for both very high and low elevation angles. Deviations in the balloon's ascent rate are translated into horizontal wind speed errors. In summary, the single theodolite system is of practical use in obtaining limited resolution vertical profiles of horizontal wind in the lowest few kilometers of the atmosphere.

- <u>Multiple Theodolite</u>

Multiple theodolite tracking of balloons has been used to obtain more detailed wind profiles than are possible with single theodolite observations (e.g., Ackerman, 1974). The balloon position, given geometrically by the intersection of lines from the theodolites, is independent of any assumption of the balloon's vertical motion or any form of atmospheric equilibrium. Since there are always some errors in the observations, the most common method for solution is to follow Thyer (1962) who positions the solution along the line connecting the points of closest approach between the rays defined by the theodolite angles. Radio-theodolites allow observations during cloudy days and, with large baseline separations, up to stratospheric heights. Nelson (1973) has analyzed data collected from GMD-2 and WBRT-60's operated in a triangular array approximately 50 km on a side. Even though equipment accuracy specifications implied an uncertainty in positioning of 40 to 80 m for any two rays of total length 50 to 100 km, observed errors were an order of magnitude larger. Nelson attributed these errors to a combination of antenna alignment problems and to overly optimistic equipment accuracy specifications. The former will yield a systematic or absolute error while the latter will produce a random positioning error. The random error is of greater significance if one wants to look at turbulence structure. Smaller baselines between radio-theodolites will reduce the effects of errors caused by both systematic and random error components for times near launch. However, errors in balloon positioning at large distances and upper tropospheric or stratospheric heights will increase.

- Angle Positioning with Thermodynamic Heights

This method has been used historically by the Weather Service and others to determine air motion with the radiosonde (rawinsonde). Knowledge of the thermodynamic state parameters allows integration of the hypsometric equation to determine height which together with elevation and azimuth angles yields the balloon position. Errors in wind will arise from errors in the measured angles as well as errors in height due to inaccuracies in the numerical integration of the hypsometric equation or departures of the atmosphere from hydrostatic balance. The GMD series of tracking systems have been the standard in radiosonde tracking for about a quarter century. Commonly accepted rms positioning errors are 0.05° in azimuth and elevation angles for elevation angles above 15°, though Danielsen and Duquet (1967) show evidence of occasionally larger and nonrandom angular deviations from the true position which can persist for several minutes. The assumption of a uniform ascent rate between standard pressure contact levels can also lead to errors in determining statistics of the horizontal wind field. All in all, errors in the horizontal wind of ± 1 m s^{-1} are typical over one minute intervals when angular data is sampled ten times each minute. Tracking angles below 15° produce larger errors due to ground reflection and refractive index variations. Clearly, this technique is unsuitable for tracking constant-level balloons.

- Angle Positioning with Passive Ranging

Passive ranging of a balloon sensor has been demonstrated to be one of the more accurate methods of determining small-scale atmospheric motion. Sophisticated radars like the FPS-16 have been able to resolve motion on scales smaller than the natural induced oscillations of rising standard meteorological balloons. Equipment specifications give rms accuracies of $.01^{\circ}$ in azimuth and elevation and five meters in slant range. However, Scoggins and Armendariz (1969) discuss some of the practical limitations in accuracy of the FPS-16 radar system. Operator adjustments and data smoothing procedures are very important for optimizing data quality. DeMandel and Krivo (1972) have determined the frequency at which most of the variance

in the observations can be attributed to atmospheric motion rather than radar noise. They found that structure with a vertical scale of 10 meters was resolvable at heights of 5 km, however, at 15 km, only structure with a vertical scale over 100 meters is observable. Also, as is the case with all angle positioning devices, errors are substantially increased at low elevation angles. This technique has been used to track constant-level balloons as well as rising balloons.

- Angle Positioning with Active Ranging

Another method of balloon positioning is to attach an active device (transponder) to the balloon for ranging purposes. This technique used in conjunction with an M-33 radar has allowed accurate tracking of low level tetroons to distances of 105 km by research teams at the National Reactor Testing Station (NRTS) in Idaho Falls, Idaho (e.g., Angell, et al., 1968). Estimates of errors associated with this system have been made by simultaneously tracking a single tetroon with two M-33 radar systems. These data give results of rms system errors of about 30 meters in range and nearly 0.10° in azimuth and elevation angles. These numbers translate into instrument errors of about 2.5 m s^{-1} in the horizontal wind and 1 m s^{-1} in the vertical air motion over periods of 30 seconds. Much of the M-33/tetroon data is smoothed over time periods of two to three minutes.

- Navigational Aids Positioning

Within the last ten years a new type of wind measuring system has been developed which makes use of already existing VLF and LF frequencies available for general navigation. Principal Navigational Aids (Navaids) used so far include OMEGA (10-14 KHz) and Loran (around 100 KHz) transmissions. Many papers [e.g., Acheson (1970), Beukers (1972), Beukers (1973)] have been published describing Navaid systems and associated accuracies. The Omega system can be used over extensive areas of the globe but is limited to accuracies of horizontal wind of around 1 m s^{-1} over four minute periods and 3 m s^{-1} for one minute averages (Lally, 1972). Loran systems

have accuracies of around 0.5 m s^{-1} for one minute intervals (Beukers, 1975) but geographical coverage is limited. Vertical motion and height are determined thermodynamically as with a radiosonde. The greatest advantage of the Navaid system is for tracking balloons at sea, as it does not depend upon the expensive stable platforms required by all other systems.

- Doppler Radar

Doppler radar systems can be used to determine fine-scale velocity structure indicated by balloon sensors. A feature of this type of system is that the radial velocity of the target is measured directly. Doppler systems such as the one discussed by Lhermitte (1967) have the capability of measuring the instantaneous radial velocity of spherical balloons to about 0.5 m s^{-1}. A problem with using a Doppler radar to look at small-scale velocity structure is that a single system can only detect one component of the velocity field. Three systems separated in space and looking at the same target are necessary to obtain the three-dimensional velocity field.

- Doppler Positioning

Recently, a new type of Doppler positioning system which has the capability of looking at very fine scale atmospheric velocity structure has been demonstrated. This system, the METRAC™ positioning system, will be described in more detail in the next chapter. Here it will suffice to say that the METRAC system eliminates most of the problems inherent in angle measuring systems. Problems of refractive ray bending are minimized, and areal separation of system components allow very accurate positioning over extended distances although, as will be shown later, this accuracy is dependent upon system geometry.

4.2 BALLOON AERODYNAMICS

An evaluation of the accuracy of fine-scale measurements of atmospheric winds from balloon systems requires consideration of the aerodynamics of balloons.

- <u>Self-Induced Oscillation of Rising Balloons</u>

It has been known for decades that rising rubber balloons undergo self-induced motions even in still air. Although some investigators have attributed these motions to deformation of the balloons, it is now known that rigid plastic balloons also suffer self-induced oscillations. Murrow and Henry (1964) have performed a number of experiments on several prototype balloons which elucidate the extent of the problem. Their experiments consisted of tracking ascending balloons in Hangar Number One at the Lakehurst, New Jersey, Naval Air Station. The balloons tested included standard radiosonde balloons, 2-meter mylar spherical balloons, streamlined balloons and roughened balloons. All balloons tested exhibited self-induced oscillations although some reduction in amplitude of oscillation was achieved by significantly roughening the surface of balloons.

The theory behind the self-induced oscillation is far from complete but it is generally understood that the oscillations are the result of periodic x and y directed aerodynamic lift forces which result from vortex shedding in the unstable wake of the balloon. According to Fichtl (1971), as long as the Reynolds number (Re = $\frac{\overline{W}D}{\nu}$; where $\overline{W}$ is the average rate of vertical ascent, D is the diameter of the balloon and ν is kinematic viscosity) is below a critical value of 2.5×10^5, a rising spherical balloon will exhibit an orderly spiral motion with a vertical wavelength of close to twelve balloon diameters. However, for super-critical Reynolds numbers, the balloon's self-induced motion becomes erratic. For a spherical balloon of two meter diameter with an average vertical velocity of five meters per second in the standard atmosphere, the Reynolds number will be super-critical below 11 km and subcritical above.

The Jimsphere is a spherical super-pressure balloon (Scoggins, 1965), the surface of which has been covered by roughness elements. The Jimsphere has been developed by NASA and used in conjunction with radar to obtain fine-scale wind measurements below 18 km which is its maximum altitude. The

purpose of the roughness elements is to control the random vortex shedding process which sends smooth balloons into erratic self-induced motion. The erratic aerodynamic oscillations typically have periods of five seconds and amplitudes of a few m s^{-1}. The Jimsphere does not eliminate these oscillations. Rather, they become more sinusoidal in character. As a result, it is easier to retrieve from wind profiles fine-scale structure of a scale equal to or less than the scale of the aerodynamically induced balloon oscillations. However, in the subcritical Reynolds number regime in the stratosphere the Jimsphere may offer little advantage over a smooth balloon.

- Balloon Response

Self-induced oscillations discussed above are the result of the interaction of a moving balloon with its own wake. It remains to consider the response of the balloon to variations in the environmental wind field through which it passes. Fichtl (1971) has made a linear perturbation analysis of the response of the Jimsphere to a vertically varying wind field. His analysis indicates that in the troposphere the Jimsphere is responsive to vertical variations in the wind field on the order of 10 m. Furthermore, Fichtl's analysis shows that the Jimsphere becomes less responsive at higher altitudes. The analysis was not continued above 18 km and there appears to be no corresponding analysis for smooth balloons. Fichtl et al. (1972) have also considered the behavior of spherical balloons in wind shear layers and concluded that the Jimsphere may suffer a horizontal "velocity defect" as large as .6 m s^{-1} in the lower stratosphere.

The response of tetroons to changes in the environmental wind field has been considered by several authors. The primary factor limiting the response of the tetroon to air motion is the restoring force of the balloon when it is carried away from its level of static equilibrium. Hanna and Hoecker (1971) have considered the response of constant-density balloons to sinusoidal variations in the horizontal plane of vertical wind speeds. Because of the restoring force, the balloon's vertical motion is less than the vertical motion of the air. More significantly, for sinusoidal motion the phase of the tetroon oscillation leads the phase of the air motion. These effects are

most pronounced for low frequency oscillations. For example, a sinusoidal vertical air motion with an amplitude of .5 m s^{-1} and a period of 10^3 sec will cause the balloon oscillation to lead the sinusoidal air motion by 30^o and the vertical velocity of the tetroon to be only 5% less than the vertical velocity of the air. These results suggest that the analysis of flux data from turbulence statistics derived from tetroon data should be viewed with caution for periods greater than 10 or 15 minutes. Although horizontal velocities of the tetroon should be fairly representative of air motions, vertical velocities may be slightly underestimated and correlations between horizontal and vertical velocities may be poorly estimated. It is commonly assumed that horizontal and vertical velocity fluctuations measured from tetroon data are representative of air motions with periods of order several minutes or less. However, it should be noted that the sensitivity of the tetroon to the smallest scales of turbulence will decrease with altitude as density decreases.

4.3 DIFFUSION COEFFICIENTS FROM FLUX-GRADIENT RELATION

If measurements of momentum flux are available simultaneously with a vertical wind profile then it is possible to estimate diffusion coefficients from flux gradient relations. According to this approach the vertical diffusion coefficient is defined by

$$\overline{uw} = -K_Z \frac{\partial \overline{U}}{\partial Z} \tag{4.1}$$

where $u = U-\overline{U}$ and $w = W-\overline{W}$ are the departures from the mean of the longitudinal and vertical components of the wind.

The vertical eddy momentum flux can be determined from tetroon data and the gradient of the mean wind can be evaluated from any wind profile data available. One possibility for deducing K_z from a single balloon flight is to use the data from a tetroon approaching its "constant" flight level.

4.4 DIFFUSION COEFFICIENTS FROM LAGRANGIAN VELOCITY VARIANCE STATISTICS

According to the theory of atmospheric diffusion as developed by Taylor (1921) the spread of smoke or some other passive additive can be related to the variance of turbulent atmospheric winds. Thus, in one dimension

$$\sigma^2 = \overline{u^2}T^2 \tag{4.2}$$

for small diffusion time T where σ is the half width of the cloud. If we define a one-dimensional diffusion coefficient K by the relation

$$\sigma^2 = 2KT, \tag{4.3}$$

then for small diffusion times

$$K = \frac{\overline{u^2}}{2} T \tag{4.4}$$

and it is possible to determine three-dimensional diffusion coefficients from the variance of measured velocity fluctuations

$$K_X = \frac{\overline{u^2}}{2} T \tag{4.5a}$$

$$K_Y = \frac{\overline{v^2}}{2} T \tag{4.5b}$$

and $$K_Z = \frac{\overline{w^2}}{2} T \tag{4.5c}$$

where $u = U - \overline{U}$, $v = V - \overline{V}$, and $w = W - \overline{W}$ are the departures from the mean of longitudinal, lateral and vertical velocities. A more general formulation of the one-dimensional diffusion is given by Taylor (1921) as

$$\sigma^2 = 2\overline{u^2} \int_o^T \int_o^t R_\ell(\tau)d\tau dt \tag{4.6}$$

where $R_{\ell}(\tau)$ is the Lagrangian auto-correlation function defined by

$$R\ (\tau) = \frac{\overline{u(t)\ u(t+\tau)}}{\overline{u^2}}. \tag{4.7}$$

Clearly, the Lagrangian autocorrelation function will have its maximum value for $\tau = 0$ and will decrease with lag τ as the velocities become uncorrelated. If $R(\tau) \sim 1$, as is the case for small T, Equation 4.6 leads to 4.2.

For general T it is useful to define

$$I(T) = \int_0^T R_{\ell}(\tau)d\tau \tag{4.8}$$

which has a value in the range $0 \leq I(t) \leq T$. I(T) is dependent upon the structure of the Lagrangian turbulence spectrum. When the diffusion time exceeds the time scales for which there is any appreciable turbulent kinetic energy for a particular velocity component, the value of I(T) approaches an asymptotic value I* which is an integral diffusion time scale. In general this diffusion time scale will be different for each velocity component.

If, following Taylor, the turbulence is assumed to represent a stationary random process, then

$$K_X = \overline{u^2}\ I_X\ (T) \tag{4.9a}$$

$$K_Y = \overline{v^2}\ I_Y\ (T) \tag{4.9b}$$

and

$$K_Z = \overline{w^2}\ I_Z\ (T) \tag{4.9c}$$

define three-dimensional diffusion coefficients for arbitrary diffusion time.

In the limit that the diffusion time becomes much longer than the time scale of the Lagrangian correlation function then the diffusion coefficients will approach asymptotic values

$$K_X = \overline{u^2}\, I_X^* \tag{4.10a}$$

$$K_Y = \overline{v^2}\, I_Y^* \tag{4.10b}$$

and $$K_Z = \overline{w^2}\, I_Z^* \quad \text{for large T.} \tag{4.10c}$$

Moreover, since $\overline{w^2}$ will be much less than either $\overline{u^2}$ or $\overline{v^2}$, it is not surprising that K_Z values are many orders of magnitude less than K_X or K_Y for global diffusion problems.

4.5 DISCUSSION

In this chapter a review has been presented of the application of balloon techniques to the measurement of small-scale turbulence and diffusion in the atmosphere. Several different approaches to tracking rising and floating balloons have been discussed and several problems involving the aerodynamics of rising and floating balloons have been considered. Two techniques have been presented for deriving quantitative diffusion coefficients from measured atmospheric winds.

Until recently the most accurate technique for observing detailed atmospheric wind fields has been to track a Jimsphere with a radar such as the FPS-16. Endlich and Davies (1967) have explored the feasibility of using the FPS-16, Jimsphere system to measure turbulence in the free atmosphere. They concluded that the radar data showed sufficient resolution to observe fluctuating winds associated with light-moderate turbulence. No quantitative technique was presented to obtain turbulence parameters or diffusion coefficients from tracking ascending Jimspheres.

Any technique which employs vertically rising balloons suffers a major difficulty. Rising balloons simply do not stay in the same volume of air long enough to obtain representative turbulence statistics. To be sure, it is always possible to analyze the detailed structure of the vertical profile measured by the rising balloon. Nevertheless, it is extremely difficult to interpret the product of such an analysis.

The most promising technique for obtaining quantitative turbulence measurements and diffusion coefficients involves the tracking of constant-level balloons. The floating constant-level balloon is carried in a trajectory which approximates the flow of the mean wind. High-resolution tracking data enables the separation of fluctuating longitudinal, transverse and vertical velocity components from mean values. Diffusion coefficients can be obtained from an analysis of Lagrangian turbulence statistics as outlined in Section 4.4.

Velocities of less than 1 m s^{-1} must be observable. This precision is beyond the capability of most balloon-tracking systems discussed in this chapter without averaging over time periods of a minute or longer. Averaging over these periods is marginal for resolving turbulence of the vertical wind whose primary components include time scales of a few minutes.

5. METRAC™ BALLOON TRACKING SYSTEM

5.1 DESCRIPTION OF THE METRAC SYSTEM

The METRAC system is based on the Doppler shift of a moving transmitter. Although the physical principles are well known, only the recent availability of low-cost digital components and UHF-VHF transistors have permitted an economically feasible electronic design. The METRAC system uses omnidirectional antennas for both transmitting and receiving and does not require mechanical or electronic scanning. This eliminates the elaborate pedestal and drive assemblies associated with dish antenna tracking systems.

The basic elements of the METRAC system are an airborne transmitter and several receiving stations having known positions. As the transmitter moves in space, the frequency at each receiver equals the transmitted frequency plus a Doppler frequency shift, which is a linear function of the velocity of the transmitter. Because the true transmitted frequency may not be known, this Doppler shift cannot be determined from only the data at one receiver. However, the data from any pair of receivers permits a determination of the difference of received frequencies. Since these receivers are at rest with respect to each other, the frequency difference equals the difference of the Doppler shift associated with the receiver pair. This Doppler difference is the only data required to determine the transmitter position relative to the receivers.

The integrated Doppler difference associated with each pair of receivers is directly proportional to the slant range difference from the transmitter to each receiver. A known slant range difference determines a hyperbolic line of position on which the transmitter is located. The receivers are the foci of this hyperboloid. The data from three independent receiver pairs (four receivers) determines the transmitter position in space.

The electronics required to implement the system consists of an inexpensive balloon-borne transmitter, four or more receivers, and a central command console. The command console is used to record the Doppler data to determine the transmitter position. The METRAC system using six receivers is shown schematically in Figure 3. All receiver coordinates must be known accurately. An audio frequency communication link is used between the central command site and all receivers. A stationary radio transmitter generates a reference frequency; its coordinates are unimportant except that it must have a direct line of sight to each receiver.

The balloon transmitter frequency, f_t, is nominally 403 MHz, which was chosen because this frequency falls in the band allocated for meteorological aids. The reference frequency, f_{ref}, is kept about 2 KHz different from the balloon frequency by means of feedback from one of the receivers. Radiation from both transmitters is used by each receiver to form an output signal whose frequency f_{roi} is given by

$$f_{roi} = f_t + d_i - f_{ref} . \tag{5.1}$$

where d_i is the Doppler shift observed at this i^{th} receiver. The signal to noise ratio is sufficiently large to permit multiplying this difference frequency by eight, thereby increasing resolution. The frequency is counted, repetitively sampled and stored on magnetic tape at the command console.

The Doppler difference for any receiver pair yields

$$\Delta f = f_{roi} - f_{roj} = d_i - d_j . \tag{5.2}$$

The difference in counts given by 5.2 is used by the computer to solve for balloon position at the time of the samples, assuming that the intital location of the balloon is known accurately.

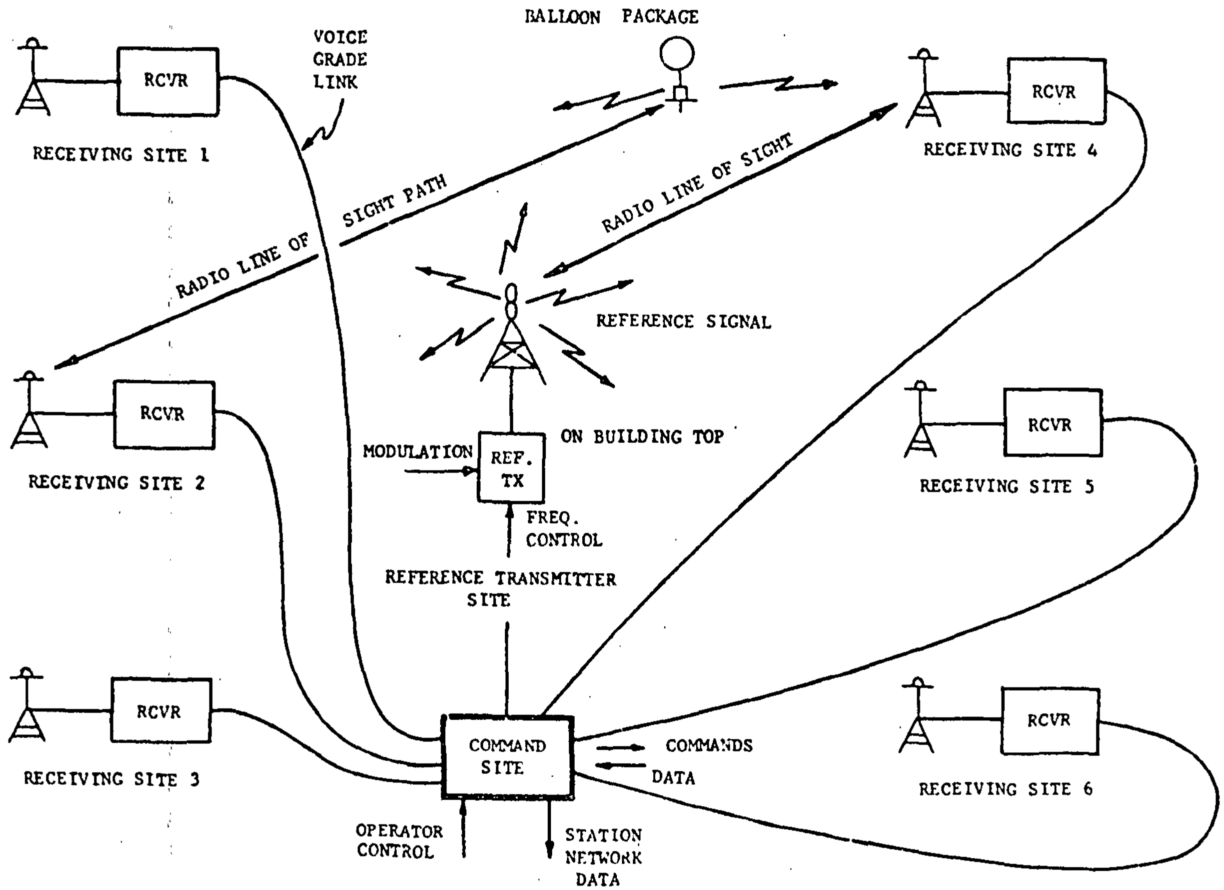

Figure 3. Schematic representation of the METRAC system deployment.

5.2 THE METRAC SYSTEM ACCURACY

The Doppler differences obtained by forming the differences of frequencies received by pairs of receivers are the input to the METRAC solution algorithm. The transmitter location is obtained from this algorithm in a fashion similar to the solution of hyperbolic equations employed in common navigational problems. The potential accuracy of the METRAC system is determined by the effective wavelength of the transmitted signal and the geometry of the receiver array.

- System Geometry

The basic measurement unit of the METRAC system is the wavelength, λ, of the transmitted signal. Consequently, the maximum number of distinguishable hyperbolic surfaces between two receivers separated by a distance D is D/λ, and the transmitter position is determined to be on one of these surfaces. Increased resolution can be achieved by multiplying the received frequency by a factor M. The basic measurement unit is then λ/M, denoted by λ_M, and the system accuracy increases as M increases. For a physically realizable multiplication factor of 8, λ_M corresponds to a resolvable distance of approximately 10 cm at 403 MHz.

As can be seen in the two-dimensional example illustrated in Figure 4, the spacing between hyperbolic shells depends upon geometrical position. Only on the line between each pair of receivers is the separation of the shells as small as λ_M. Clearly, the accuracy of the computed position depends upon the spacing of the shells as well as the orientation of the foci (receivers) with respect to each other and to the position of the transmitter. Maximum practical three-dimensional resolution is achieved by deploying an equally spaced ring of receivers about a central receiver. A minimum receiver array should consist of a triangle of receivers with a fourth in the center. The centrally located station is very important in giving good vertical resolution. When there are more than a minimum set of four receivers operating properly over some time interval, some of the solutions will be better than others because of the differences in the geometry.

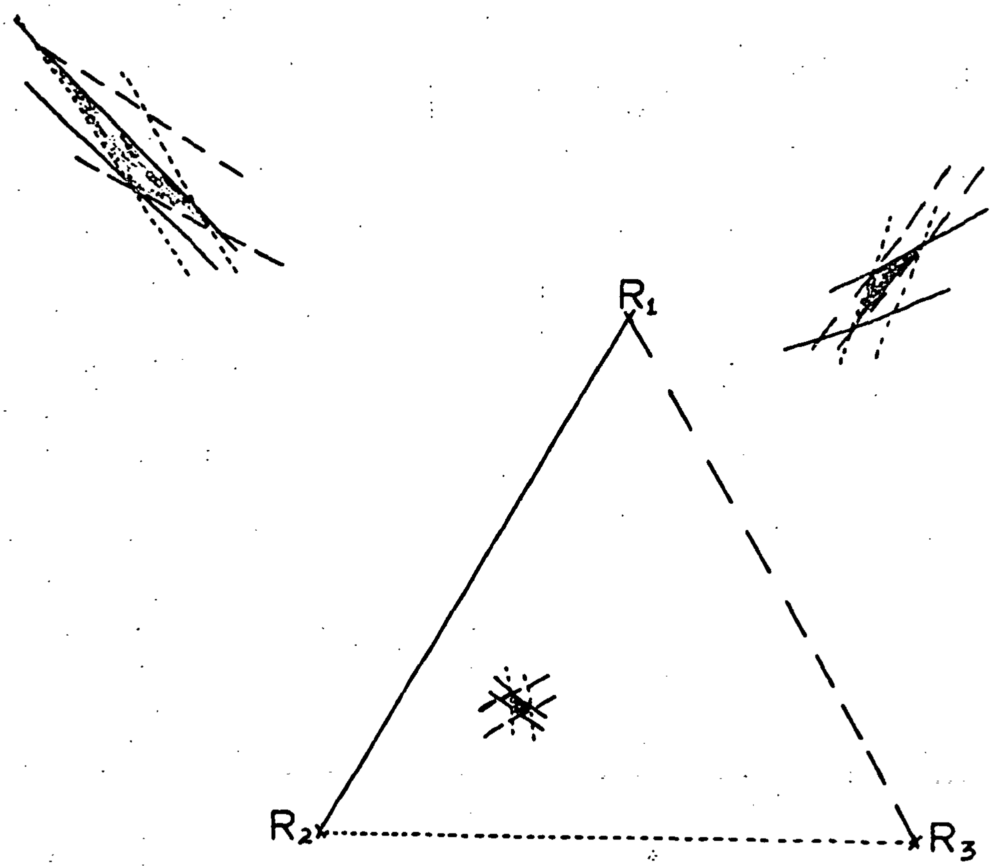

Figure 4. Two-dimensional examples of position uncertainty as determined by the intersection of hyperbolic shells.

The two-dimensional example of Figure 4 also shows that the hyperbolic shells tend to become more nearly parallel to one another well outside the borders of the receiver array. This implies that the uncertainty in computing position of the transmitter grows as the balloon drifts away from the array. The uncertainty is largest in the radial direction. Increasing the averaging times in determining the winds when the balloon is well outside the station array will decrease the effect of the position uncertainty.

- <u>Sources of Error</u>

There are two primary sources of error which can affect the METRAC solution: count errors and station location errors. Count errors can come from a variety of sources, some interrelated. The most serious errors would arise if either the balloon or reference transmitter were interrupted even momentarily. This would cause dropped counts at all receiver stations simultaneously so that no solution could be computed.

Count errors will also occur if the frequency difference (reference and balloon transmitter) tracking filter loses lock at any receiver. This will happen whenever the signal to noise ratio at the receiver becomes sufficiently small for an appreciable part of the time constant of the filter. Experience during field tests of a prototype METRAC system showed that this situation occurred most often when the transmitter was high and nearly directly above a receiver station or when the transmitter was far (30-100 km) from the receiver. If the signal to noise ratio becomes small for a very short period of time, errors may occur in the counting even though the filter track remains locked to the frequency difference. Tests performed with a static transmitter showed that this type of error was generally random with magnitude of only one or two counts. Errors in Doppler counts can also occur due to sampling uncertainty. However, these errors are non-accumulative and are also on the order of only one or two counts per sample.

An error from any of these sources will locate the balloon transmitter between the wrong hyperbolic shells. If the error is not random, as is the case for the first two errors described above, the position error will grow as the balloon gets further away from the array and the hyperbolic shells get further apart. Random errors due to sampling uncertainty or occasional count errors will add artificial variance into the true position, but unless the balloon is well outside the baseline where the shells are far apart, the corresponding error in velocity is small even when computed over very short time intervals.

In addition to position errors due to inaccuracies in the count of the Doppler frequency difference, errors also arise from uncertainties in the locations of the receiver stations themselves. The solution to the METRAC positioning problem requires frequency counts at a minimum of four receivers as well as initial launch coordinates relative to the receiver array. Because of the extreme resolution inherent to the tracking system, an error of ten meters in the location of one station relative to the rest can be equivalent to as much as a 100 count sampling error. As the balloon moves away from its starting location, the position error will grow because the hyperbolic shells become more widely spaced as was discussed above.

5.3 SUMMARY OF METRAC FIELD TEST RESULTS

Field tests of the METRAC prototype system were carried out during the spring and summer of 1974. Figure 5 shows the locations on a map of the Twin Cities of the reference transmitter (X) and the seven ground receivers (R) as they were deployed for these tests. The reference transmitter was installed on top of a 780 foot building in downtown Minneapolis. The receivers were located in a variety of commercial and residental neighborhoods throughout the Twin City area and were connected to the command site by leased telephone lines.

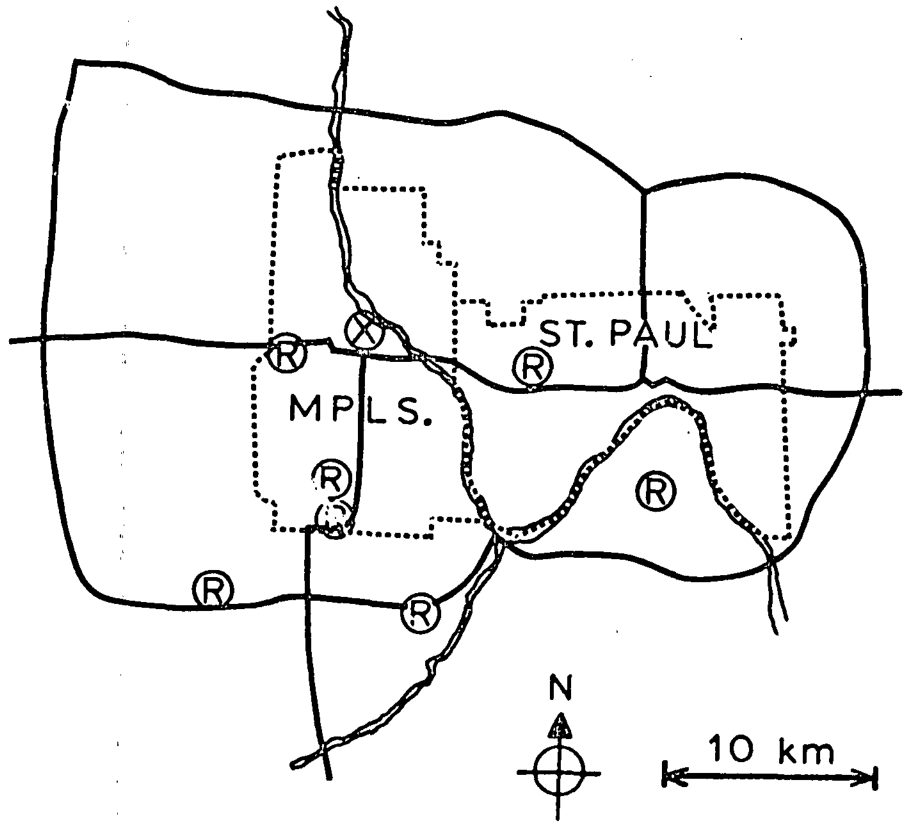

Figure 5. Minneapolis field system deployment. Each R represents the location of a receiver, X represents the location of the reference transmitter.

Tests utilizing a stationary transmitter operating for extended periods of time demonstrated that improper counting of frequency cycles or "cycle slippage" occurred only intermittently as would be expected from the discussion of the previous section and was easily detectable. Utilizing more than the minimum number of four receivers makes it possible to correct for this type of intermittent problem.

Figure 6 presents the results of an early test where a transmitter attached to a pole was carried along a prescribed path (dotted line) on the penthouse roof of a suburban hotel. Each one-second data point is plotted. The apparent systematic departure of a quarter meter may be due to the pole not being held vertically or more likely to an error in initialization. The "noise" in the track consists of both system errors and the wobble of the hand held pole. The size of these random errors agree very favorably with computer simulations of system errors.

During March and April, 1974, nine test flights of the METRAC system transmitter were made. Eight of these consisted of radiosonde comparison flights in which both the METRAC system transmitter and a standard 1680 MHz radiosonde were attached to the same balloon. The radiosondes were all tracked with a WeatherMeasure RD-65 tracking system borrowed from the University of Wisconsin. Many of these flights were also tracked with an optical theodolite. Ten additional test flights were made during June, 1974. Results from several flights have recently been published (Gage and Jasperson, 1974) and only a sample will be discussed in this report.

Figure 7 presents a comparison between 60 second METRAC and radiosonde winds (u, west-east component; v, south-north component) for the first 30 minutes of flight MF5. After an initial drift towards the ENE, the balloon traveled southward until, after 30 minutes, the balloon was approximately 10 km outside of the receiver array. The comparison between the radiosonde and the METRAC system derived winds are good below a height of 7 km after which the radiosonde winds tend to oscillate about the METRAC

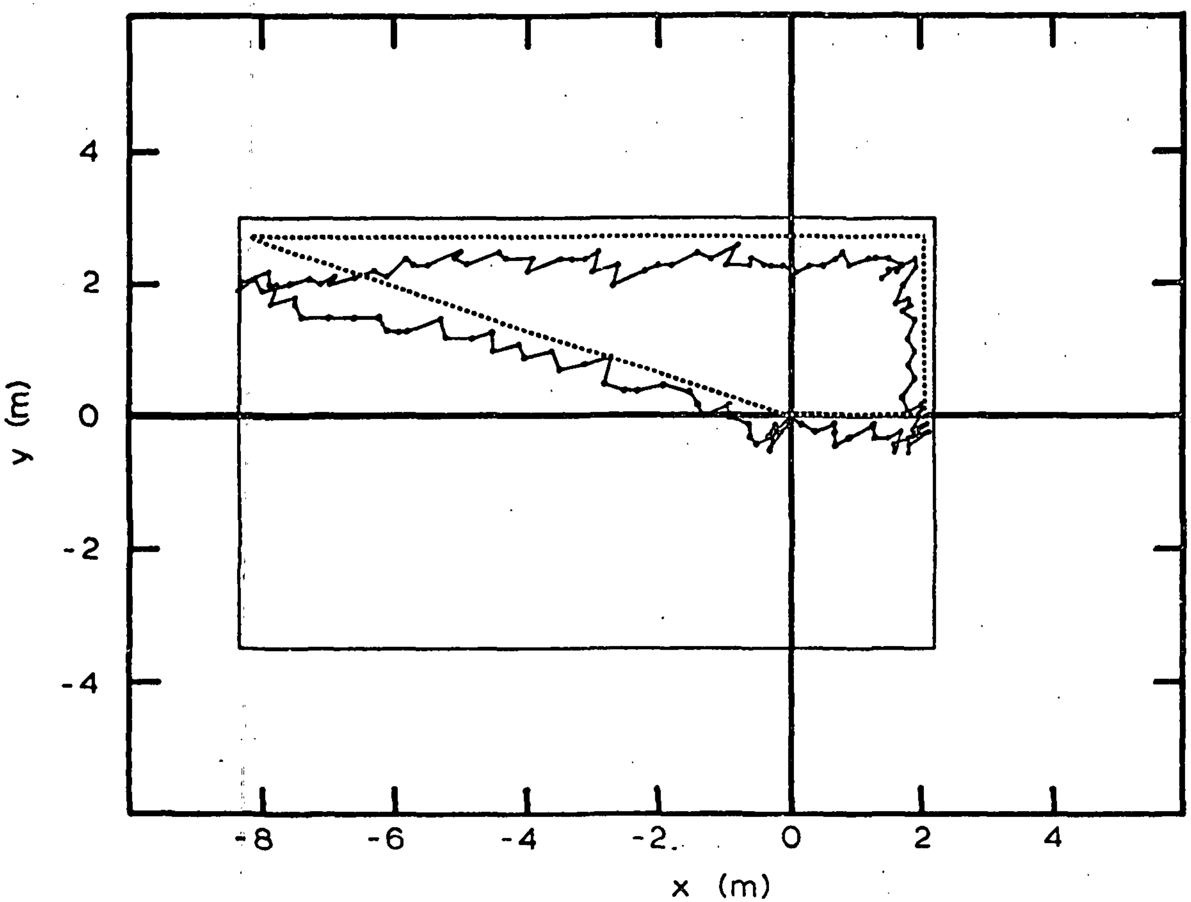

Figure 6. Trajectory obtained from METRAC system data by moving a METRAC transmitter along a prescribed path (dashed line) on the roof of a suburban hotel.

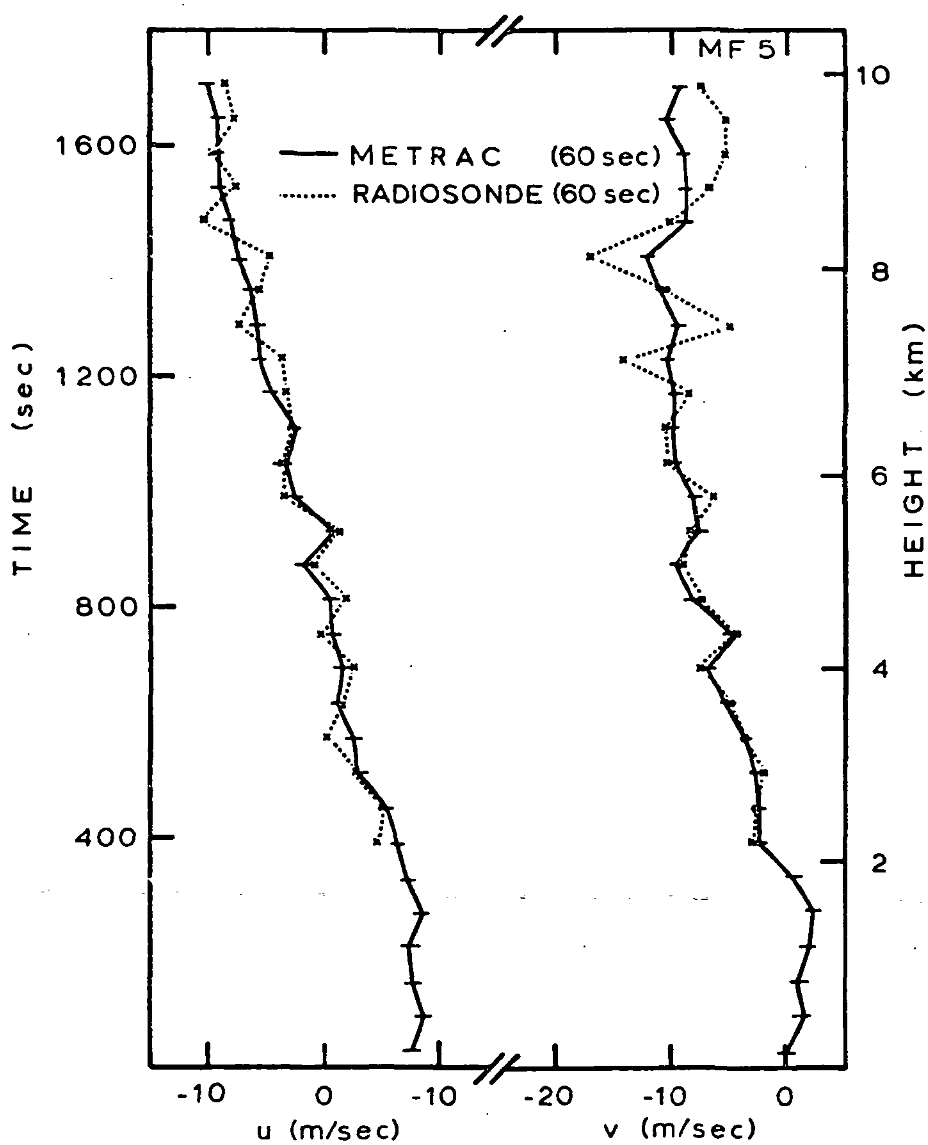

Figure 7. Comparison of 60 second METRAC system derived wind profiles with 60 second rawinsonde wind profiles. METRAC system test flight MF5 launched at 1417 CDT on 16 April, 1974.

system winds. Flight MF5 was also tracked with a theodolite and Figure 8 shows the comparisons for 20 second winds for a section of the flight. This section was chosen because of the particularly large variation found in the theodolite winds. However, the METRAC system winds confirmed the erratic wind structure except for one bad theodolite reading at 980 seconds. Because both systems were tracking the same balloon, this analysis, of course, says nothing about the time or horizontal space scale over which this large amount of wind speed structure existed. Figure 9 presents the wind profile for the same flight up to 20 kilometers in height. No comparison data is shown in this figure because of the condensed scale necessary to illustrate the detail present throughout the entire profile. A considerable amount of sharp wind velocity structure clearly exists above the tropopause height of 10.8 kilometers.

The high resolution capability of the METRAC system is further illustrated in Figure 10 which shows each one-second measure of balloon borne transmitter velocity for a one-minute dat^ sample. The regular oscillation seen in this figure shows the pendulum motion of the transmitter which was suspended several meters below the balloon.

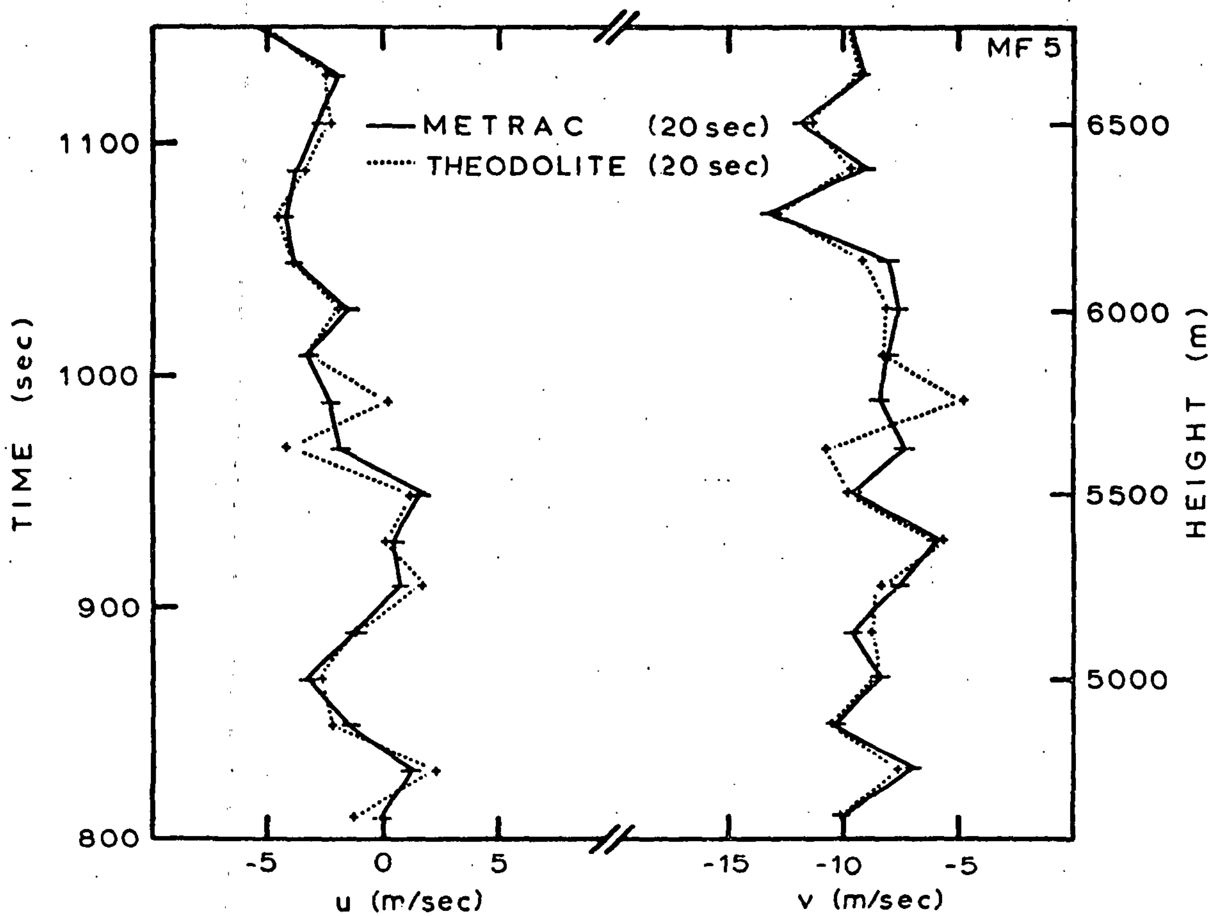

Figure 8. Comparison of 20 second METRAC system and theodolite measured winds for the section from 800 to 1150 seconds of flight MF5.

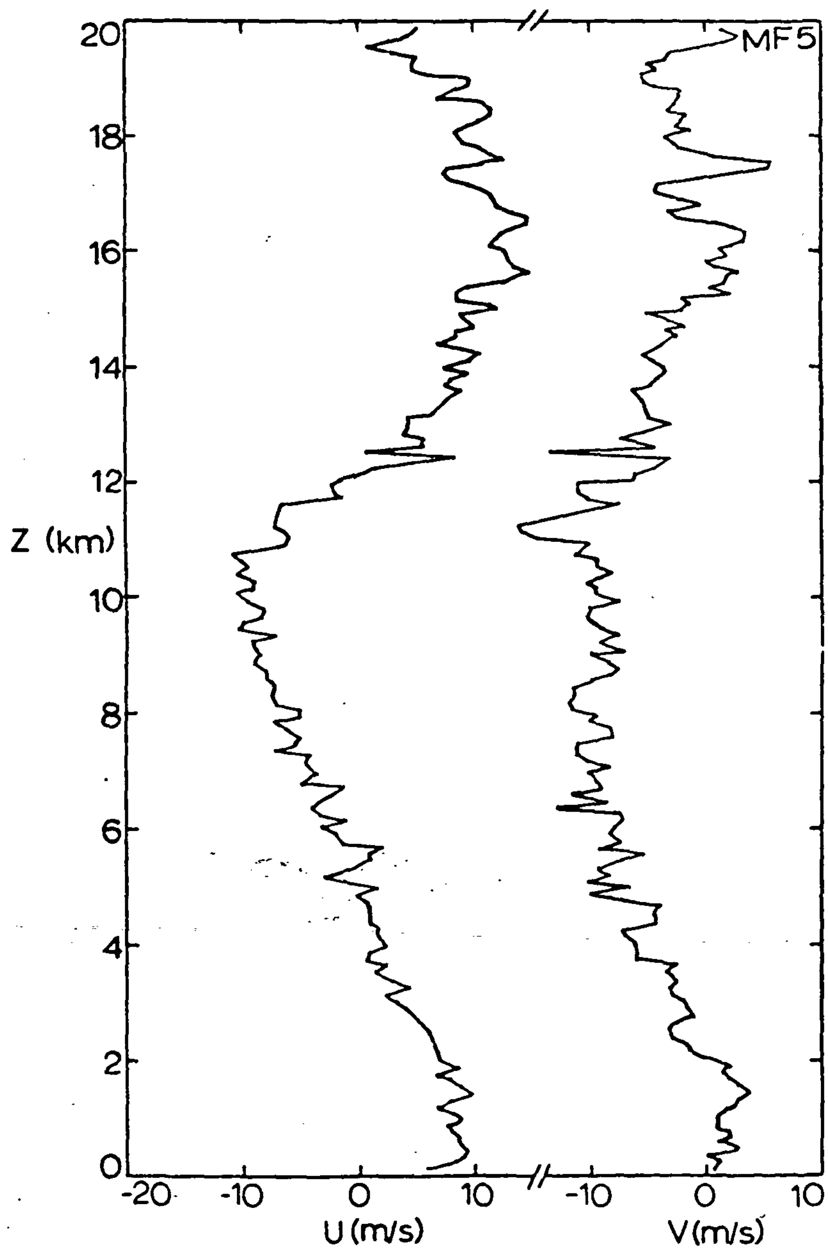

Figure 9. METRAC system measured wind profile up to 20 km. METRAC system test flight MF5.

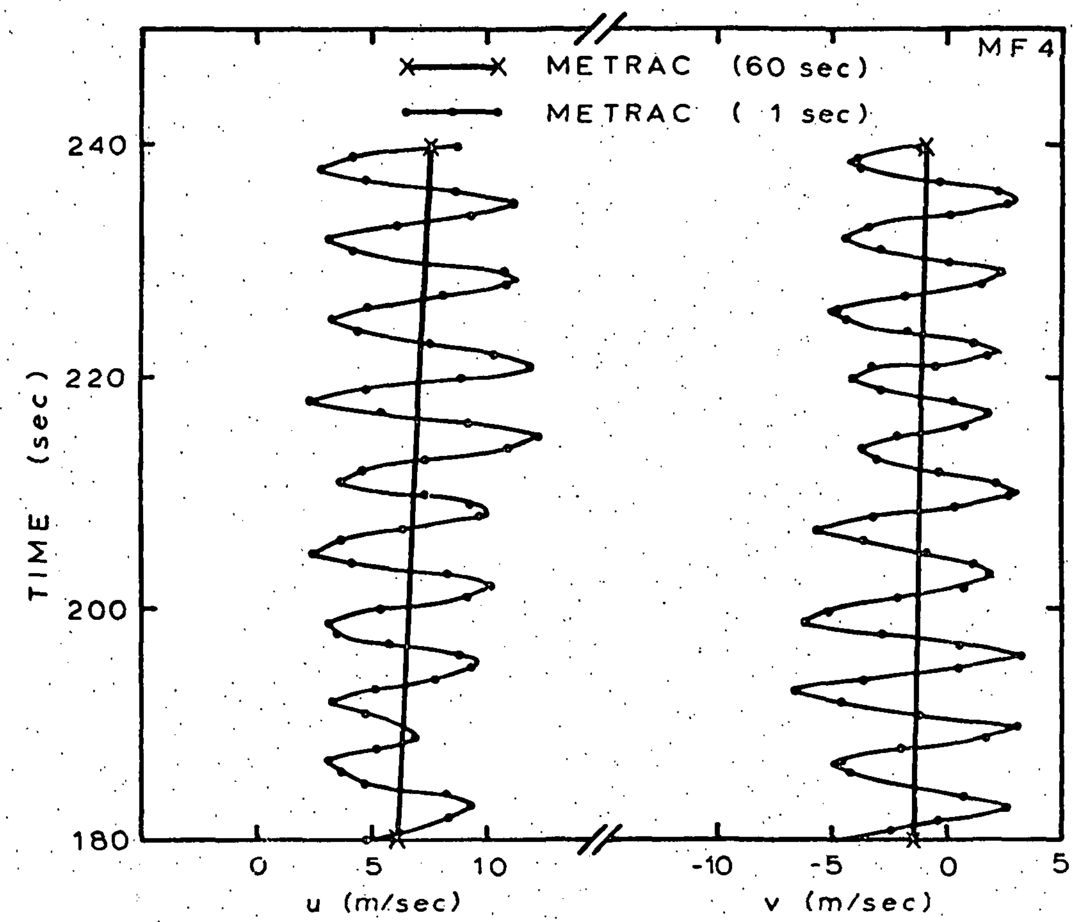

Figure 10. Balloon and transmitter package oscillations derived from one second samples of METRAC system data from MF4.

6. DIFFUSION COEFFICIENTS FROM A SAMPLE OF METRAC TETROON FLIGHT DATA

During June 1974 two constant-level balloons were launched in Minneapolis and tracked using the Minneapolis METRAC system. In this section the results of an analysis of Lagrangian turbulence statistics from a ten minute segment of MF18 are presented. The data used in this analysis are reproduced in Figure 11. At the top of Figure 11 are plotted 10 second samples of the vertical velocity between 700 and 1300 seconds after launch of the tetroon. The mean altitude of the tetroon during this portion of flight was about 1.75 km above the surface. In the middle of the figure are plotted 10-second samples of the lateral component of the fluctuating velocity. At the bottom of the figure the longitudinal component of the fluctuating velocity is reproduced.

6.1 DIFFUSION COEFFICIENT FROM FLUX-GRADIENT METHOD

The turbulent velocity data shown in Figure 11 can be used to obtain momentum fluxes. The result is plotted in Figure 12. The vertical momentum flux $\overline{uw}$ for the period of interest is approximately $.03 \times 10^4$ $cm^2\ s^{-2}$. During this segment of flight the tetroon rose 3×10^4 cm and the longitudinal component of velocity decreased roughly 10^2 $cm\ s^{-1}$. Therefore, an estimate of K_Z from the flux gradient method is given by

$$K_Z \approx -\frac{\overline{uw}}{\frac{\Delta\overline{U}}{\Delta Z}} \sim .9 \times 10^5\ cm^2\ s^{-1}.$$

There is no way to estimate K_X and K_Y from the available flux data since horizontal gradients were not measured.

6.2 DIFFUSION COEFFICIENTS FROM ANALYSIS OF VARIANCE STATISTICS

The Lagrangian velocity can be analyzed in several ways. A common approach is to form the Lagrangian autocorrelation function defined by Equation 4.7. This has been done for the first five minutes of the

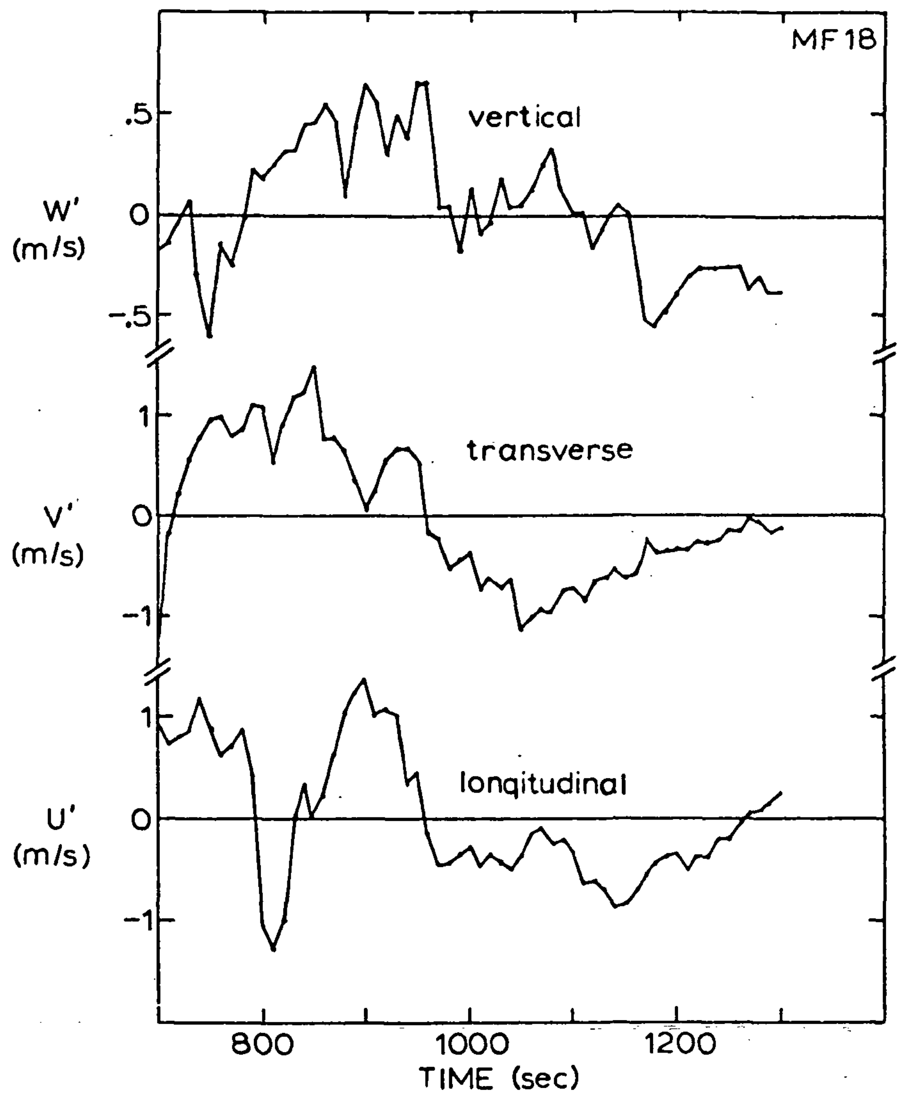

Figure 11. Departures from the mean of vertical, longitudinal and transverse velocities as measured from 600 seconds of tetroon flight MF18 launched at 1605 CDT on 13 June 1974.

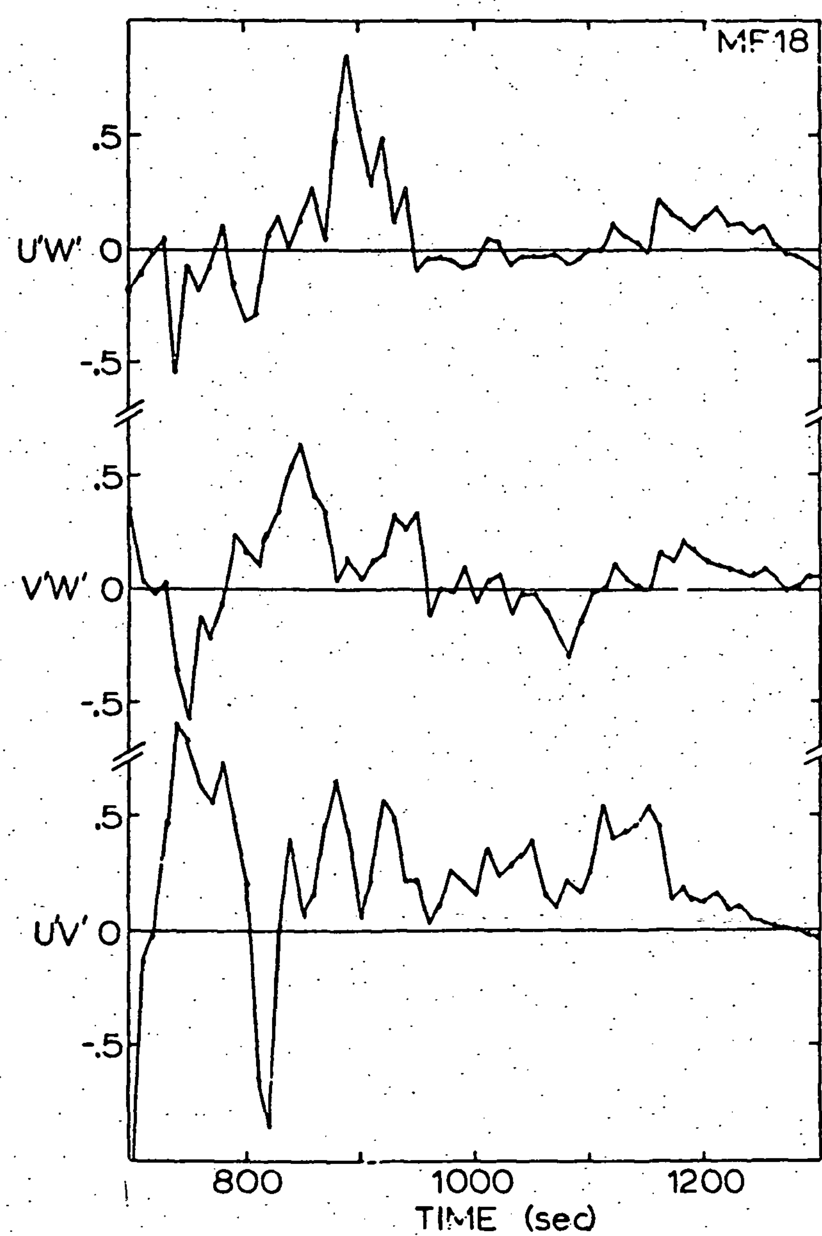

Figure 12. Horizontal and vertical momentum fluxes calculated from data presented in Figure 11.

segment of tetroon flight MF18 reproduced in Figure 11 and the results are shown in Figure 13. In this figure the normalized correlation function is plotted with lags ranging from 0 to 250 seconds. The correlation coefficient for the longitudinal velocity shows evidence of a periodic structure with a period of about 160 seconds. The transverse and vertical velocity correlation functions appear qualitatively similar with negative correlations for lag greater than 130 seconds. The variance of the 10-sec samples of fluctuating velocities were $.13 \times 10^4$ cm^2 s^{-2} for the vertical component, $.63 \times 10^4$ cm^2 s^{-2} for the transverse component and $.58 \times 10^4$ cm^2 s^{-2} for the longitudinal component. These values can be used together with estimates of I(T) to obtain estimates of the diffusion coefficients according to Equation 4.9. The results are summarized in Table 1.

TABLE 1.

DIRECTION	VARIANCE	I(T)	K
Longitudinal (X)	$.58 \times 10^4$cm^2 s^{-2}	30 sec	1.8×10^5cm^2 s^{-1}
Lateral (Y)	$.63 \times 10^4$cm^2 s^{-2}	50 sec	3.2×10^5cm^2 s^{-1}
Vertical (Z)	$.13 \times 10^4$cm^2 s^{-2}	60 sec	$.78 \times 10^5$cm^2 s^{-1}

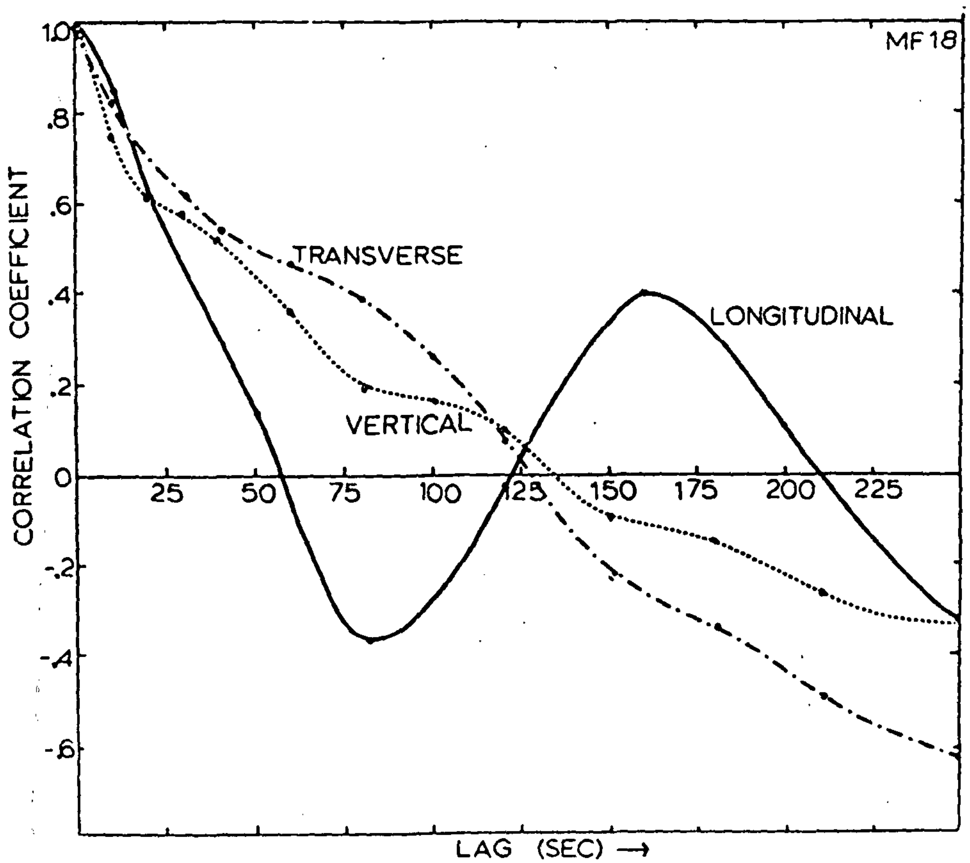

Figure 13. Lagrangian auto correlations for vertical, longitudinal and transverse components of fluctuating velocity for the first five minutes of the sample of data of Figure 11.

6.3 DISCUSSION

The high resolution three-dimensional positioning capability of the METRAC tracking system permits meaningful velocity variance data to be collected on time scales as small as a few seconds. Figure 14 presents a computer derived maximum random positioning error distribution associated with system frequency count errors of magnitude 1. Maximum positioning errors in each of the three components x (E-W), y (N-S) and z are shown with respect to the four Minneapolis field test stations (dots with lines connecting the perimeter) used to compute the tetroon statistics. The error magnitudes are valid for a one kilometer height. The arrow in the bottom third of each sub-figure shows the horizontal trajectory of the tetroon between 700-1300 seconds into the flight.

It is clear from Figure 14 that random positioning errors in x and y associated with single count errors are negligibly small. In reality as was discussed in Chapter 5, count errors are often one count or less but can through both round-off and sampling errors reach two counts. This implies maximum random errors of two meters in the horizontal and about six meters in the vertical. For 10-second sampling interval, this yields error bounds of 0.2 $m\,s^{-1}$ in the horizontal and 0.6 $m\,s^{-1}$ in the vertical. The average or expected value of this error has been determined to be about a factor of five less than the maximum errors, thus yielding expected velocity errors in all three components of less than 0.1 $m\,s^{-1}$ for the 10-second sampling intervals used in the preceding analysis. The variances in Table 1 should be in error less than 1%. The uncertainty in the diffusion coefficients given there should be dominated by the uncertainty of determining

$$\int_0^T R(\tau)d\tau.$$

The agreement between the vertical diffusion coefficient obtained from the flux-gradient method and the vertical diffusion coefficient obtained from

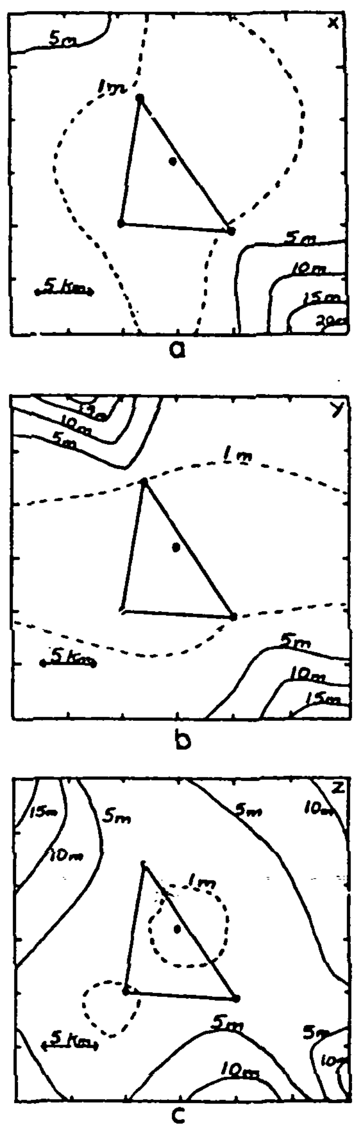

Figure 14. Maximum x (E-W), y (N-S) and z position error at one kilometer height due to integer counting of differential Doppler. The vertices of the triangle and the interior dot represent the locations of four receiver stations used in the

the Lagrangian turbulence is probably coincidental. Much more confidence can be attached to the estimate based on the Lagrangian turbulence statistics since it is undoubtedly a better measure of representative atmospheric turbulent structure. Nevertheless, a much greater sample of data would need to be analyzed in order to provide a statistically representative value of the three-dimensional diffusion coefficients which are typical for the altitude, latitude and season for which this sample was recorded.

7. APPLICATION OF THE METRAC SYSTEM FOR TRACKING CONSTANT-LEVEL BALLOONS IN THE STRATOSPHERE

The purpose of this chapter is to discuss the considerations pertinent to utilizing the METRAC balloon-tracking system to collect stratospheric turbulence data from tetroon flights. A primary consideration is to assure a high probability of a successful flight. Also, accuracy is desired at stratospheric heights. And finally, it is important to strive to achieve the maximum length of tracking time for each flight.

As was discussed in Chapter 5, a minimum number of four METRAC system receivers must operate properly over each sampling interval in order to compute a new position solution. If there are less than four receivers operating over that interval, the new position must be extrapolated from previous positions. If the sampling interval is any appreciable length of time, say even 10 seconds, extrapolation can be dangerous because all future position calculations depend upon the previous computed or assumed positions. During the Minneapolis field tests the problem of momentary receiver losses was eliminated by using seven receivers to track the balloons. Utilizing more than the minimum number of four receivers would also be necessary to assure a high probability of success for stratospheric tetroon flights.

The METRAC positioning system has an advantage over all of the traditional angle tracking systems in that velocity accuracy is not strictly a function of distance from the antenna and elevation angle. With the METRAC system the resolution is dependent upon the position with respect to the entire array of receivers. The resulting errors or error volumes may be described in many ways. Figures 15-18 present the positioning errors as a function of geometrical location with respect to a triangular array of receivers represented by open circles. They are expected or average errors associated with each full Doppler count of error. Only the errors in the x (E-W) and z directions are illustrated. Since the station array is

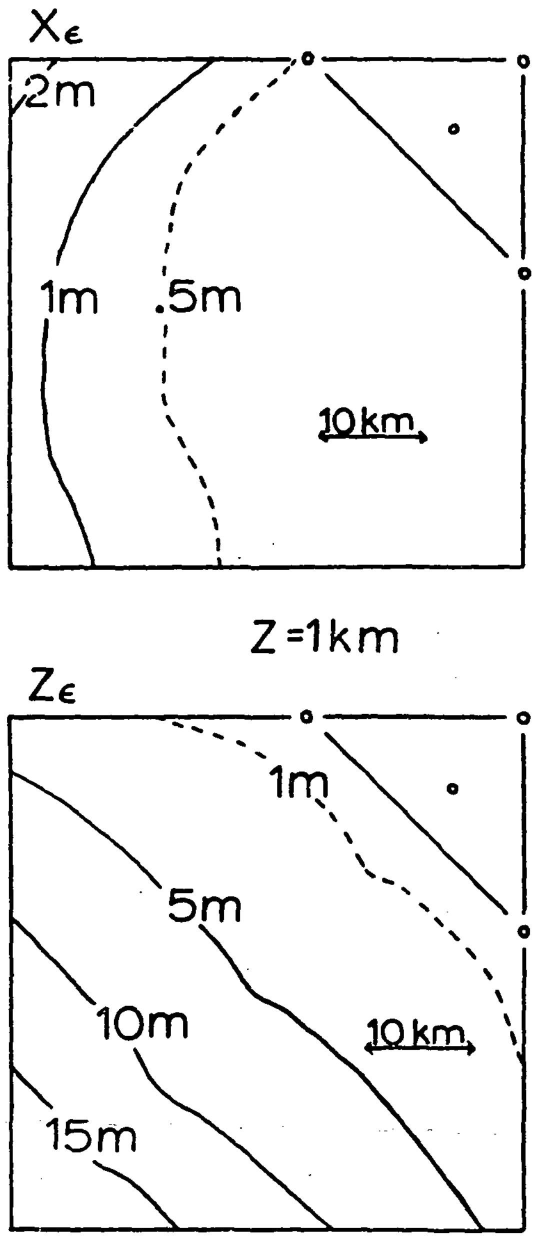

Figure 15. Horizontal distribution of expected random positioning error per Doppler count error in x (E-W) and z at a height of 1 km. The open circles represent the stationary receiver array.

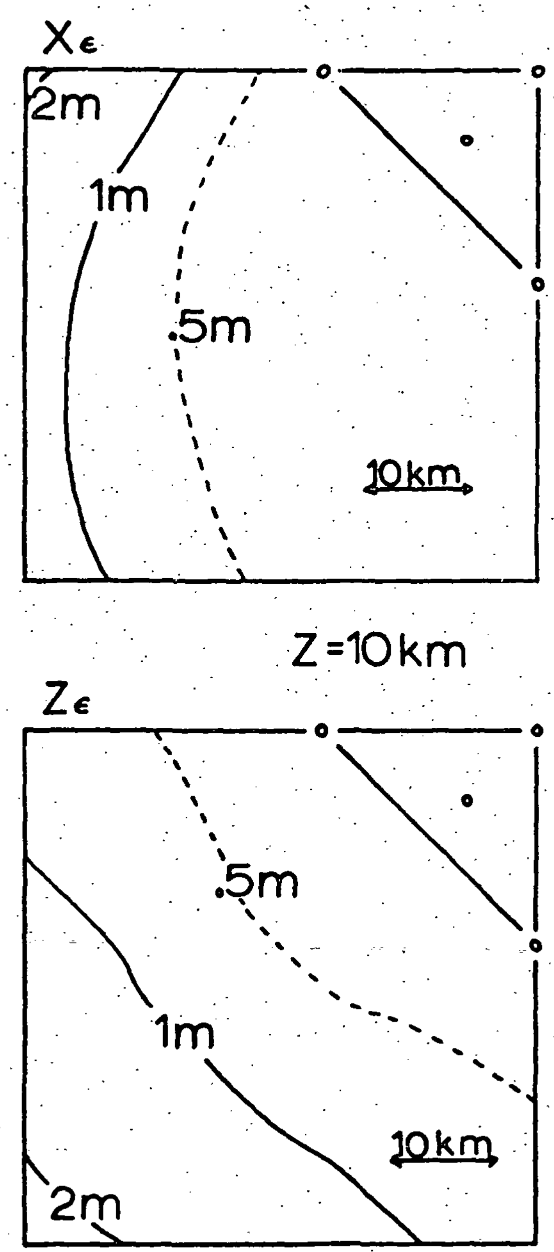

Figure 16. Horizontal distribution of expected random positioning error per Doppler count error in x (E-W) and z at a height of 10 km. The open circles represent the stationary receiver array.

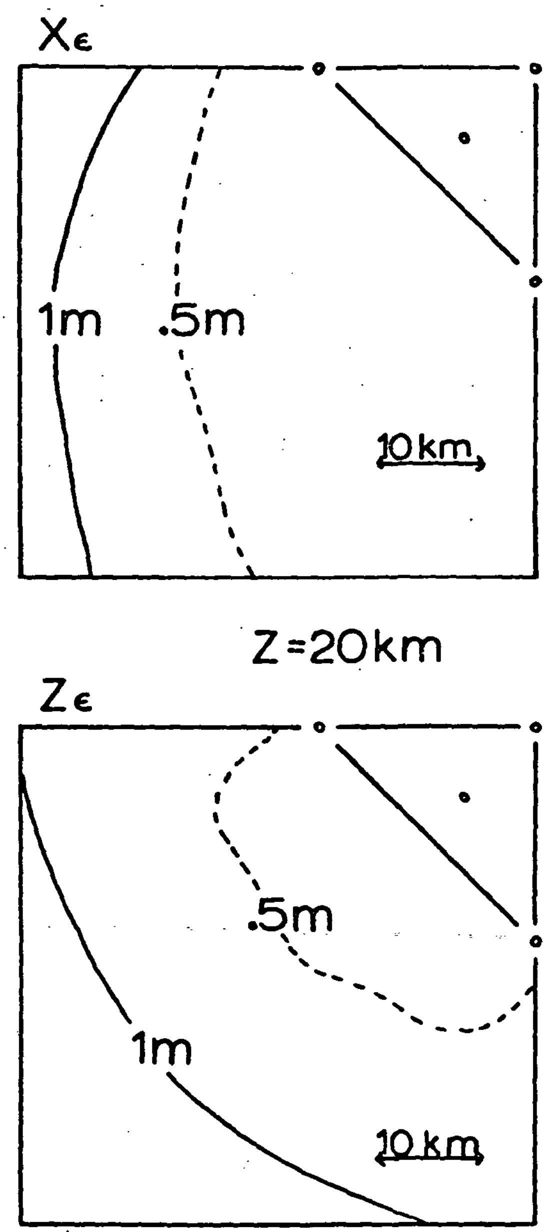

Figure 17. Horizontal distribution of expected random positioning error per Doppler count error in x (E-W) and z at a height of 20 km. The open circles represent the stationary receiver array.

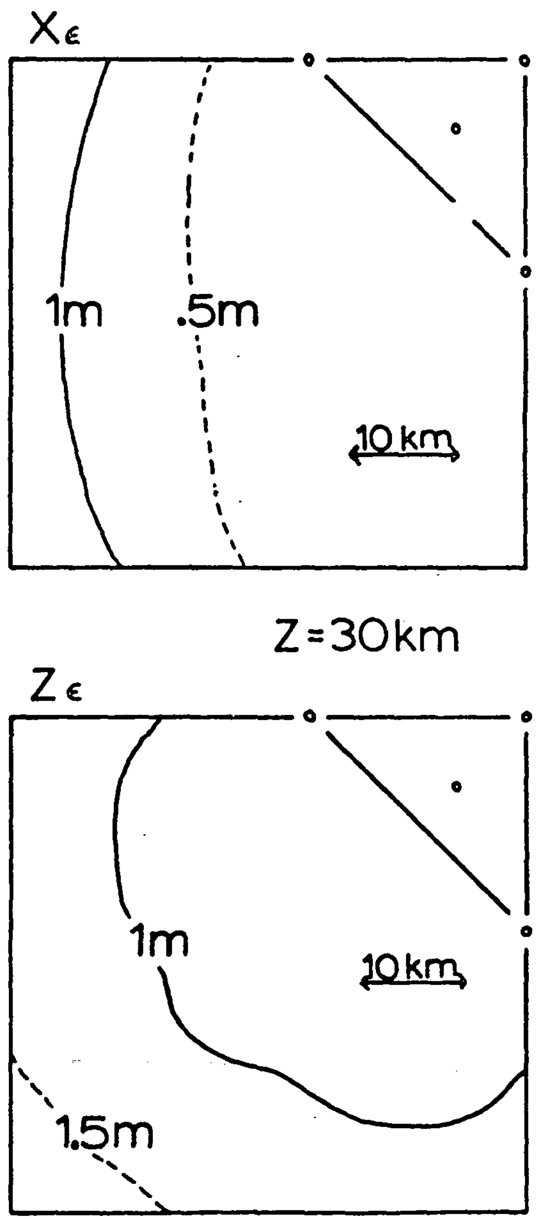

Figure 18. Horizontal distribution of expected random positioning error per Doppler count error in x (E-W) and z at a height of 30 km. The open circles represent the stationary receiver array.

symmetric, the y (N-S) errors are similar to the x errors.

Figures 15-18 show that the horizontal errors in positioning with four receivers configured in a triangular array remain reasonably consistent with height and are small at large distances from the array itself. The height errors are interesting in that they are largest at low levels outside of the receiver array. At heights of 20 to 30 km these positioning errors are less than two meters at distances several tens of kilometers away from the receiver array.

Several factors must be kept in mind in order to discuss maximizing the length of useful data for each flight. These factors will be discussed in the following paragraphs.

When discussing stratospheric turbulence, the altitude range under consideration can extend from 7 to 50 km. The lower limit in particular will depend upon the season and latitude. However, even for the lower stratospheric heights, considerable time will be required to let a normal super-pressure tetroon rise to the desired altitude. Two approaches have been used in launching tetroons. These include towing the constant-level balloon to the desirable height with a more buoyant balloon and/or releasing the tetroon upwind so that it is at or near float altitude by the time it approaches the radar site. Either of these two techniques can also be used in conjunction with the METRAC system. In the case of the upwind launch, the original launch coordinates must be known and the launch point must be within radio line-of-sight to at least four receivers. This last requirement can be more restrictive than one might desire. Some primitive computer simulations have shown that it may be possible to circumvent knowledge of the original launch location and the launch line-of-sight requirements altogether if more than four receivers operate properly for a period of time after launch. However, this has not been verified with field experiment data.

Another factor which must be considered in gathering stratospheric turbulence data with the METRAC system is that the transmitter must be able to operate without substantial power loss for extended periods of

time (1-3 hours) at very cold temperatures (-40 to -70°C). Special care should be maintained in temperature-compensating the transmitter circuitry, thermally insulating the transmitter from ambient air temperature and providing a chemical heat source for the battery power supply.

A final but very important factor which must be considered in using the METRAC system to collect stratospheric data is the receiver array design. Actually the design is determined by requirements already stated. In summary these include:

1) Redundant (more than 4) receivers

2) Triangular arrays with interior stations

3) Accurate data over long trajectories

In practice there is an implied fourth requirement: To minimize the cost of operating, maintaining and processing data from the system (i.e. minimize the number of receivers). Figure 19 presents a surface receiver station configuration which fulfills all four of these requirements. A sacrifice which is made in this configuration is that it is not symmetric. For best results the array should be oriented along the direction of the mean winds at the levels of interest. Accurate wind measurements over distances in excess of 100 km should be possible. This will yield useful statistics in Lagrangian turbulence on time scales as short as ten seconds over flight periods of one-half to three hours, depending upon the wind speed.

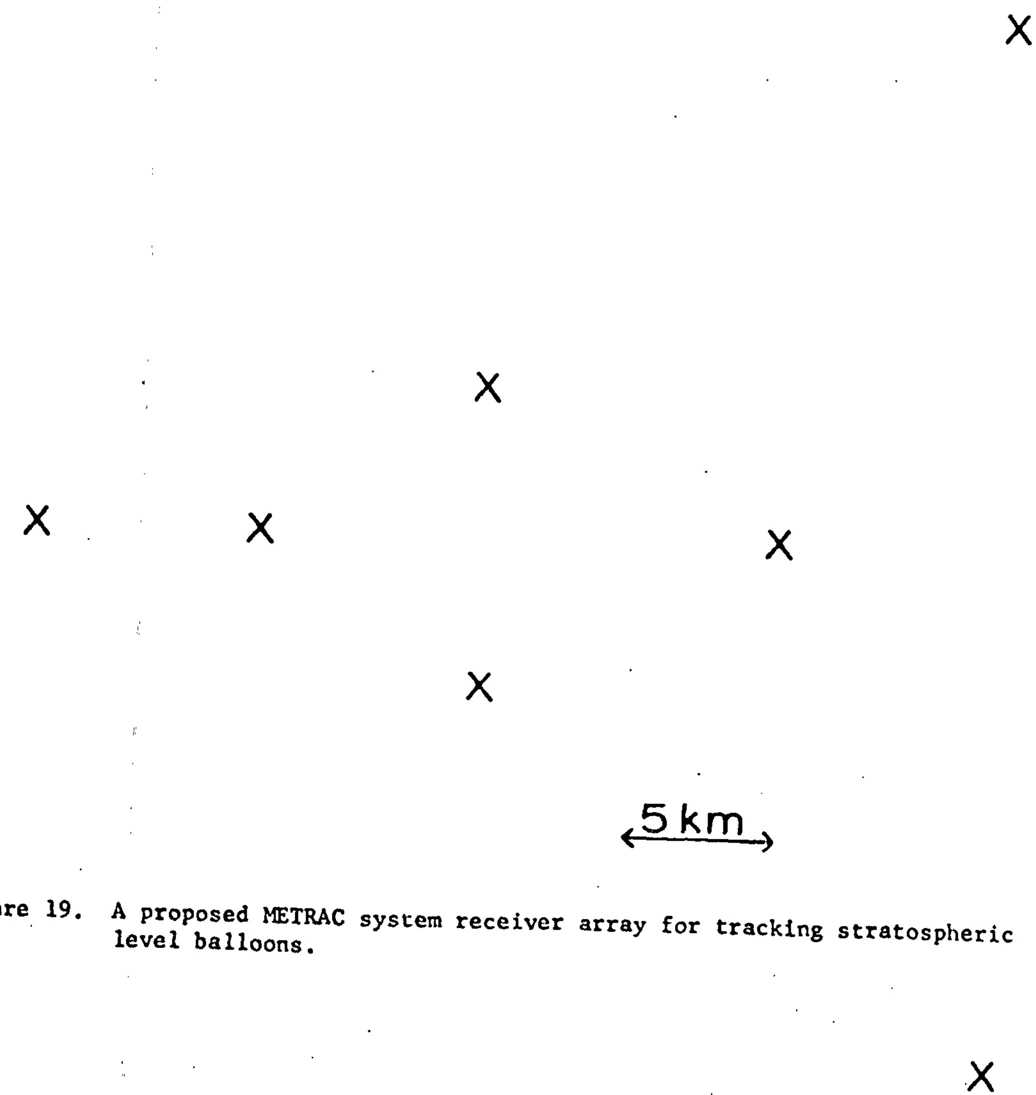

Figure 19. A proposed METRAC system receiver array for tracking stratospheric level balloons.

8. CONCLUSIONS AND RECOMMENDATIONS

This report has presented a review of the basis for present estimates of diffusion coefficients at stratospheric altitudes. Horizontal diffusion coefficients are dominated by large-scale eddy exchange processes and can be evaluated from available meteorological data. However, vertical diffusion coefficients are dominated by small-scale turbulent diffusion. The turbulence responsible for vertical diffusion coefficients has not been adequately sampled at stratospheric altitudes and only crude estimates exist of global mean vertical diffusion coefficients based on the behavior of radioactive tracers. A new technique to measure small-scale turbulence and diffusion at stratospheric altitudes is required.

From a review of alternative techniques for obtaining turbulence measurements it is concluded that high-resolution tracking of constant-level balloons at stratospheric altitudes could provide a simple, direct way of measuring Lagrangian turbulence statistics. The Lagrangian velocity variance statistics lead directly to a quantitative measure of three-dimensional diffusion coefficients.

The high-resolution capability of the METRAC system for tracking tetroons in the troposphere has already been demonstrated and a sample of the tetroon data has been included in this report. An error analysis of the positioning capability of the METRAC balloon-tracking system leads to the conclusion that this system will yield sufficient accuracy to measure turbulence at stratospheric altitudes even for data averaged over as little as ten seconds.

It is concluded, therefore, that the METRAC system can be used to obtain three-dimensional small-scale diffusion coefficients at stratospheric altitudes. It is recommended that a field demonstration be undertaken to use METRAC to collect samples of stratospheric turbulence data in order to

compute three-dimensional diffusion coefficients. If the results of the field demonstration are successful, the METRAC system should be employed to directly measure stratospheric turbulence at selected geographical locations and seasons in order to build up a climatology of the variability of diffusion coefficients.

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